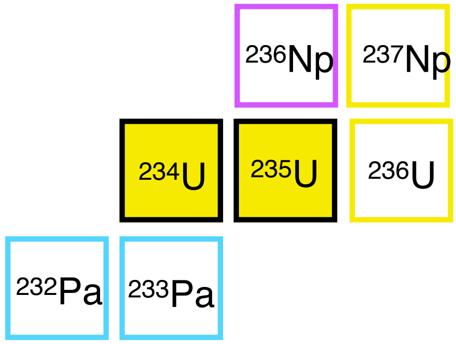

^{234}U(n,f) measurement at CERN-n_TOF

E. Leal-Cidoncha[1,3*], I. Durán[1], C. Paradela[1,4], D. Tarrío[5], L. Tassan-Got[2], L. Audouin[2], L-S. Leong[2], G. Noguere[3] and the n_TOF Collaboration

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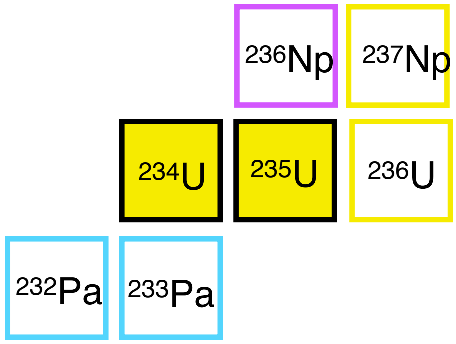
[4]EC-JRC-IRMM (Belgium)

[5]Uppsala University (Sweden)

FIESTA2017
Santa Fe, September 2017



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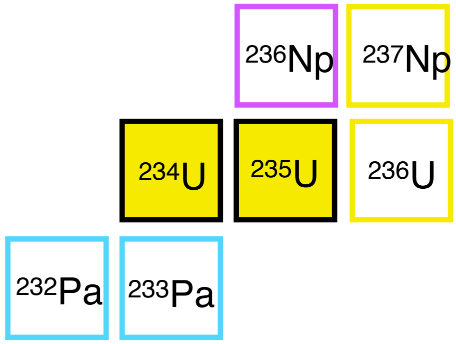
**Poster session*



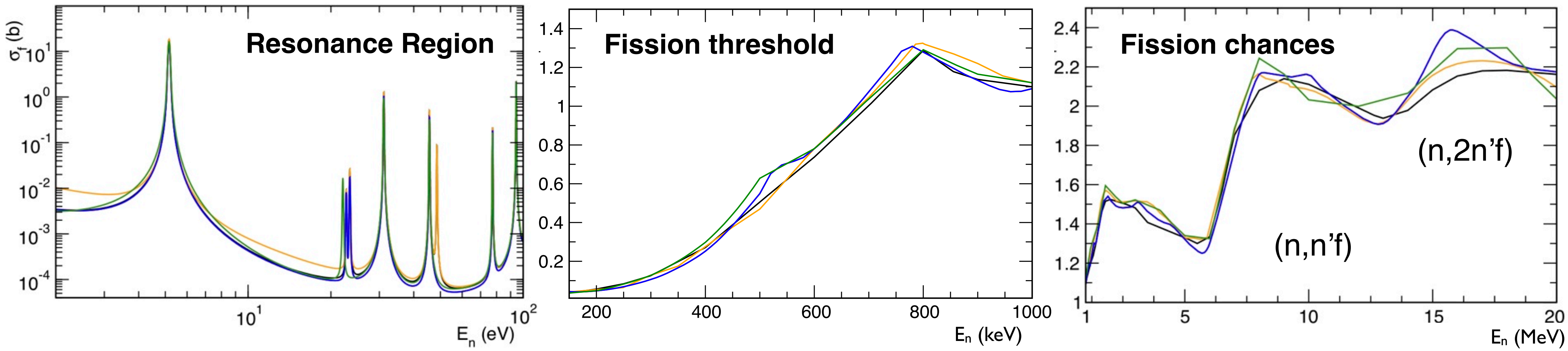
Motivation

Nuclear databases - ^{234}U(n,f)

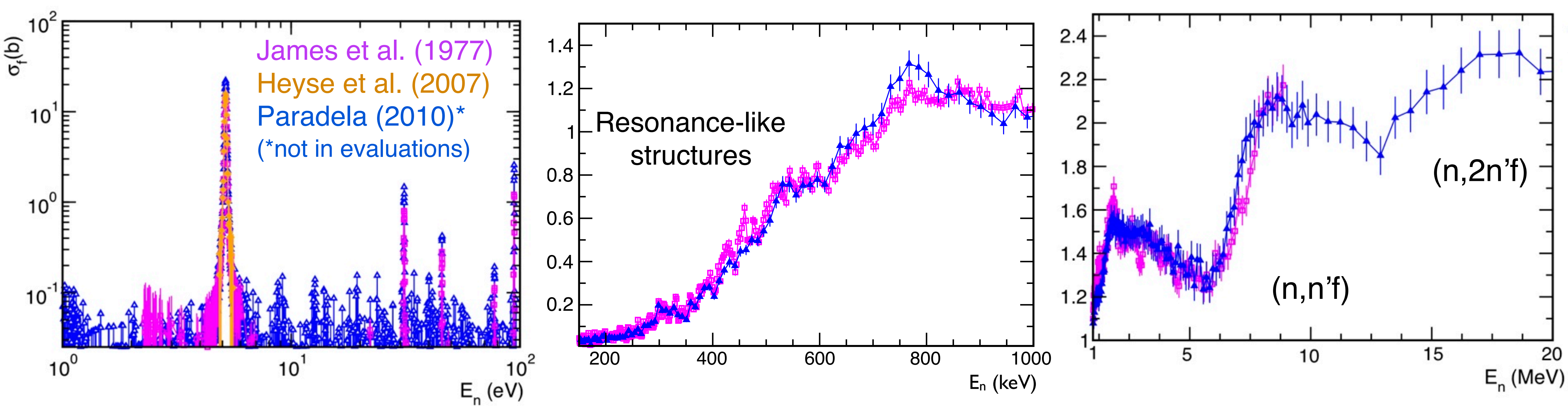
Evaluated data libraries

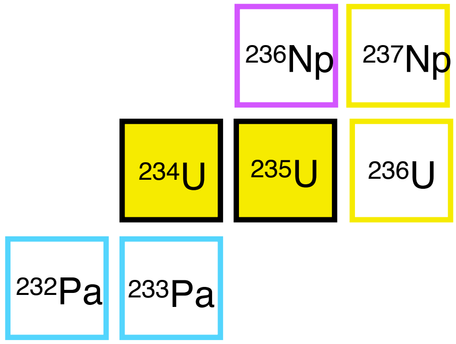
ENDF/B-VII.1 (USA) CENDL-3.1 (China) JEFF-3.2 (NEA)

JENDL-4.0 (Japan) ROSFOND-2010 (Rusia)



EXFOR (Experimental nuclear reaction data)

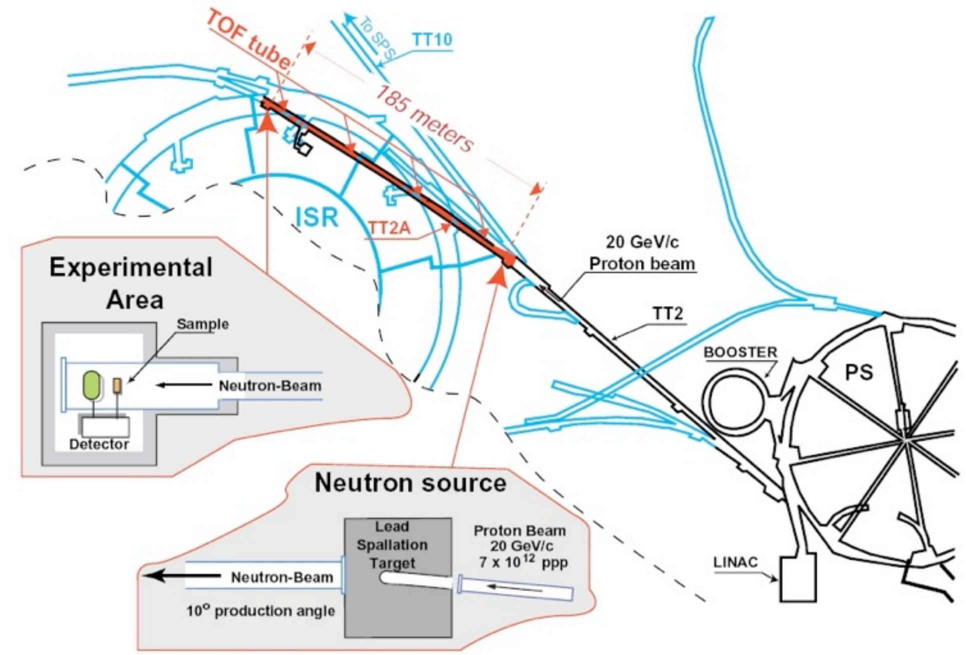




The fission detection setup (*)

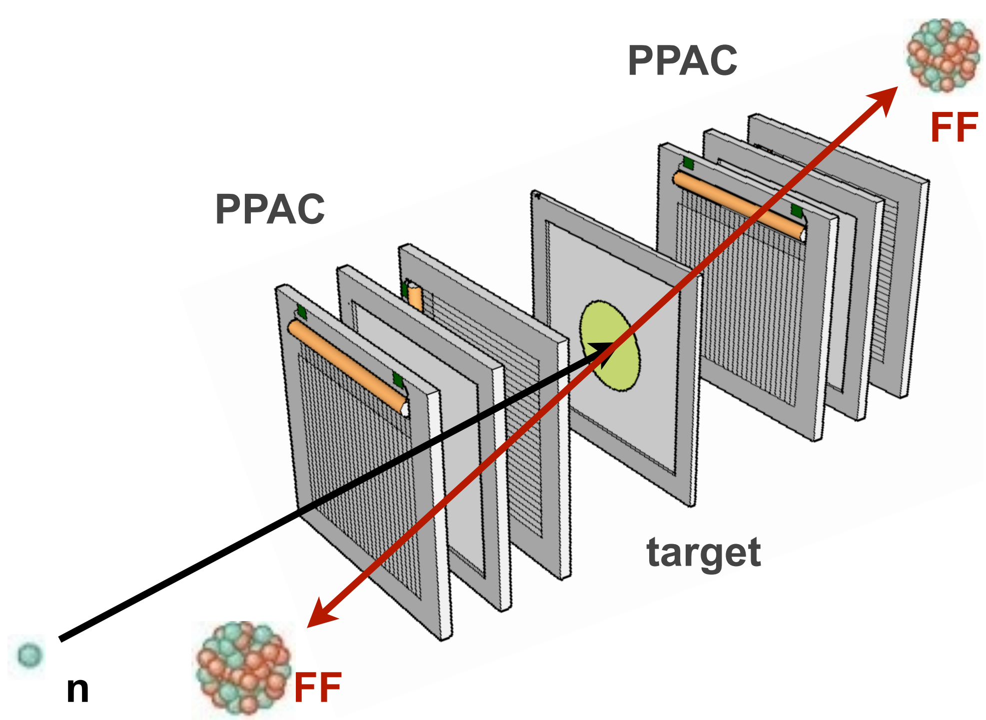
The CERN-n_TOF facility

- Proton beam (Momentum of 20 GeV/c).
- EAR1 at 182.5 m from the source.
- Wide neutron spectrum from meV to GeV.
- E_n resolution of $\Delta E/E = 5.3\cdot10^{-3}$ at 1 MeV.

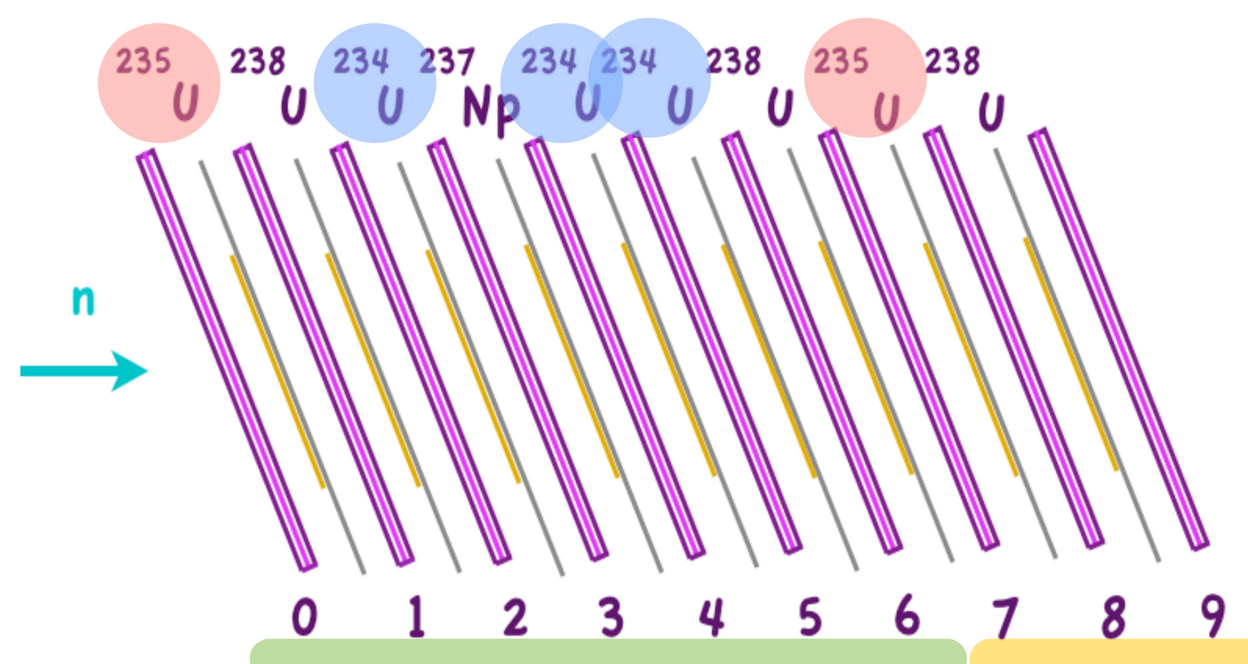


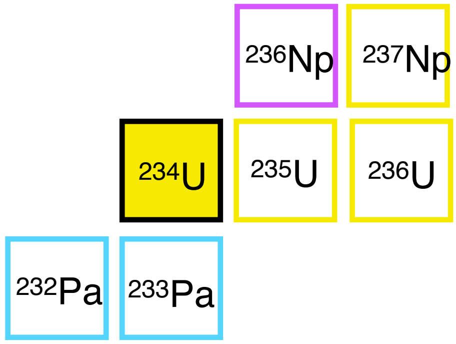
The Parallel Plate Avalanche Counters (**PPAC**)

- The central anode has a very fast signal response (time resolution ~500 ps) being used to calculate the cross sections.
- The two segmented cathodes have Al strips connected to a delay line used to reconstruct the position of the FF hit.



Detectors (10) & targets (9)





Fission Fragment Angular Distributions

FFAD at E_n < 300 MeV (*)

• The detection efficiency has been obtained from the cosine distributions at E_n < 1keV where the ^{235}U(n,f) and ^{234}U(n,f) FFAD are isotropic.

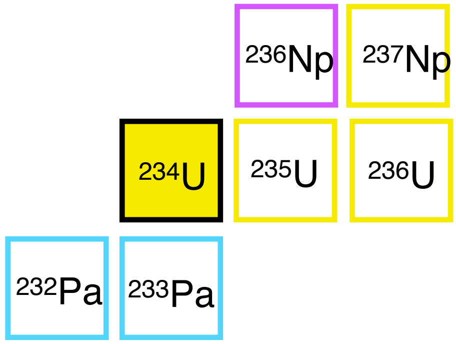
• The FFAD up to 300 MeV has been obtained **experimentally** dividing the cosine distributions by the detection efficiency at each energy interval assuming that it is constant with the energy.

• The cosine distributions have been parametrized by a sum of even Legendre polynomials in cosθ up to 4th order to calculate the coefficients (A_L).

$$W(\theta) = A_0\left[1 + \sum_{L=2}^{L_{max}} A_L P_L(\cos\theta)\right]$$

• The anisotropy parameter (A) provides a simplified description of the anisotropies with the energy and it has been calculated using the coefficients (A_L).

$$A = \frac{W(0^o)}{W(90^o)} = \frac{1 + A_2 + A_4}{1 - \frac{1}{2}A_2 + \frac{3}{8}A_4}$$

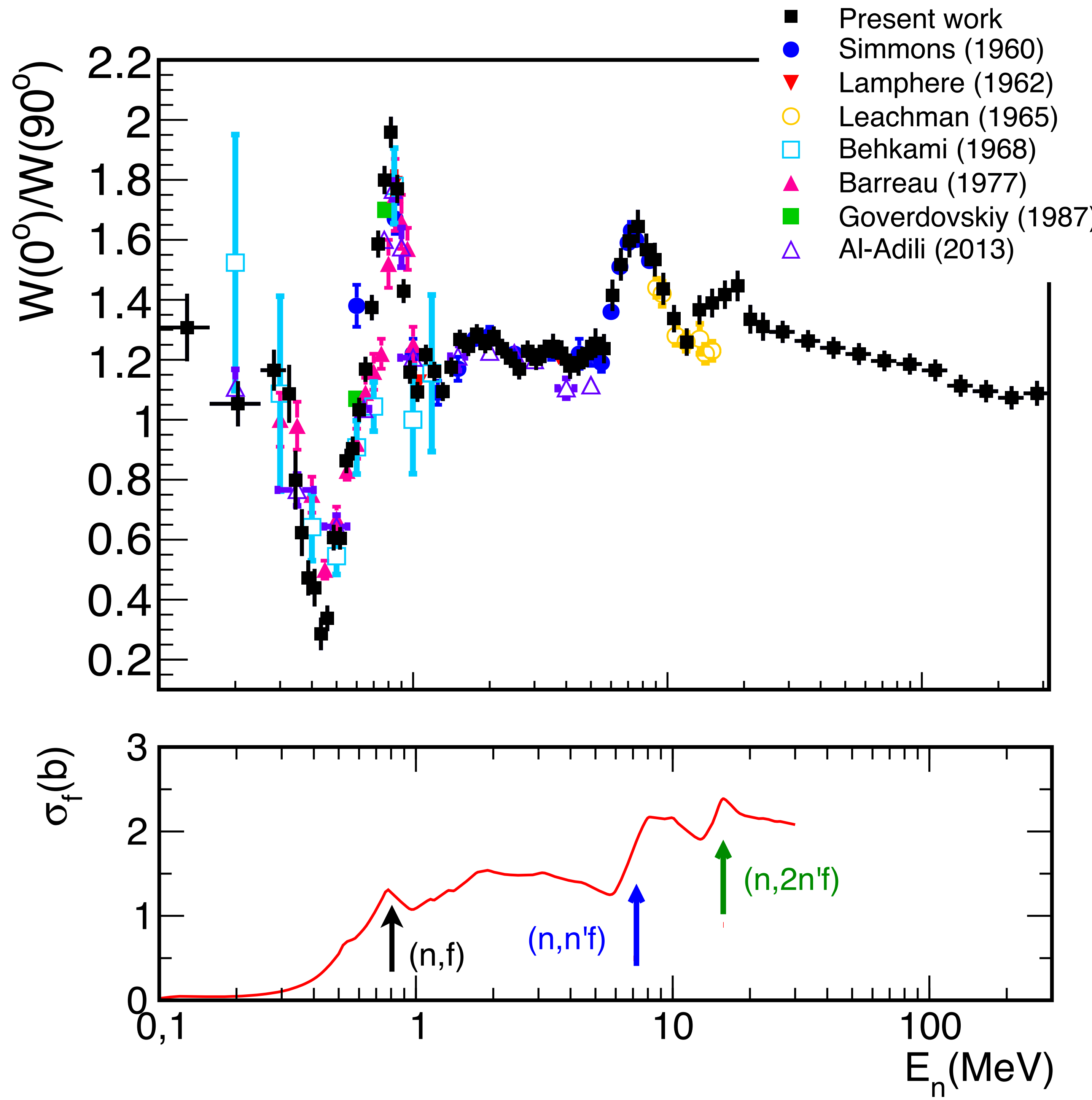


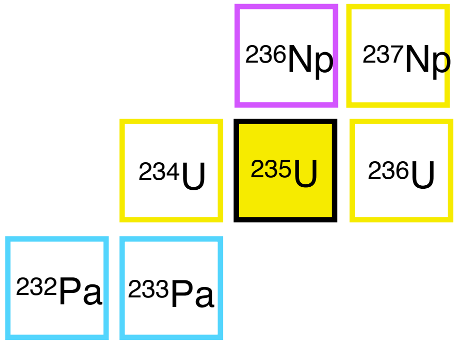
Fission Fragment Angular Distributions

FFAD at E_n < 300 MeV (*)

Anisotropy parameter - ^{234}U(n,f)

- The present data have **better resolution in energy** than previous data measured with a monoenergetic neutron beam.
- The tilted setup permits to measure from **0º-90º** obtaining more precise FFAD than previous experimental data which measured a limited angular range.
- There are not ^{234}U(n,f) experimental data in EXFOR above 15MeV.
  - In this work the third-chance is resolved for the **first time**.
  - The anisotropy parameter is provided for the **first time** in a wide energy region up to 300 MeV.



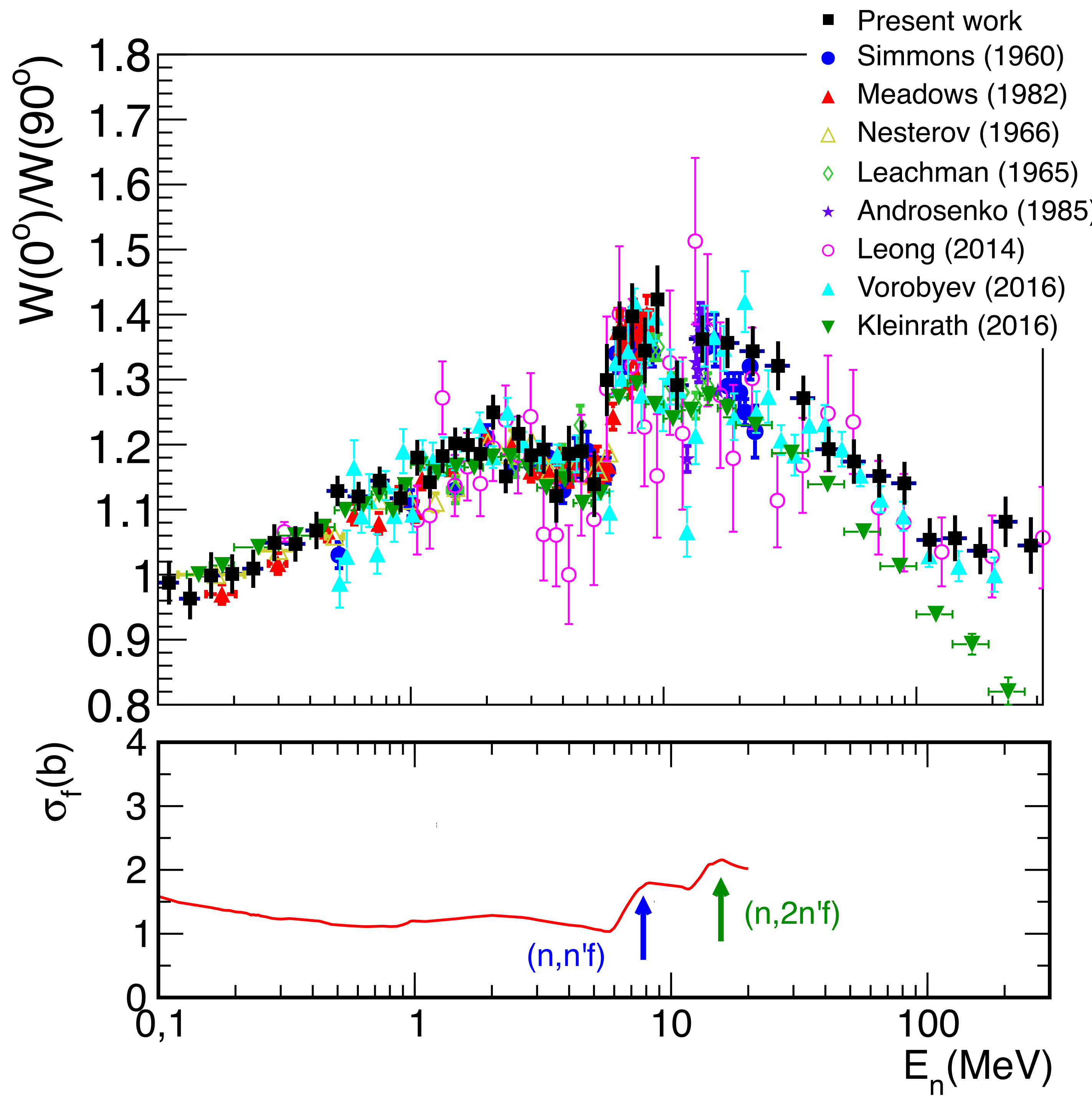


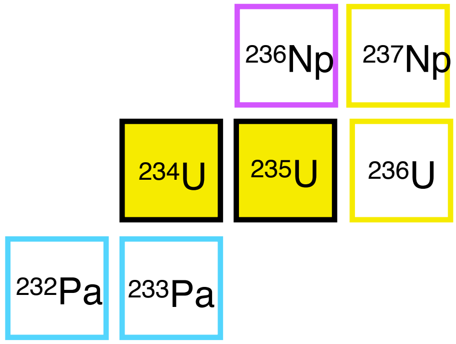
Fission Fragment Angular Distributions

FFAD at E_n < 300 MeV (*)

Anisotropy parameter - ^{235}U(n,f)

- The ^{235}U(n,f) anisotropy parameter is provided in a wide energy region up to 300 MeV.
  - Only three available data sets extends above 25 MeV:
    - These results are provided in the full angular range, while the **angular range** covered by Vorobyev was limited to 70°.
    - The present data have higher **statistics** than the n_TOF data from Leong, also measured with the tilted PPAC setup.
    - The data from Kleinrath are sistematically below the rest of datasets at the energies above the second chance threshold.





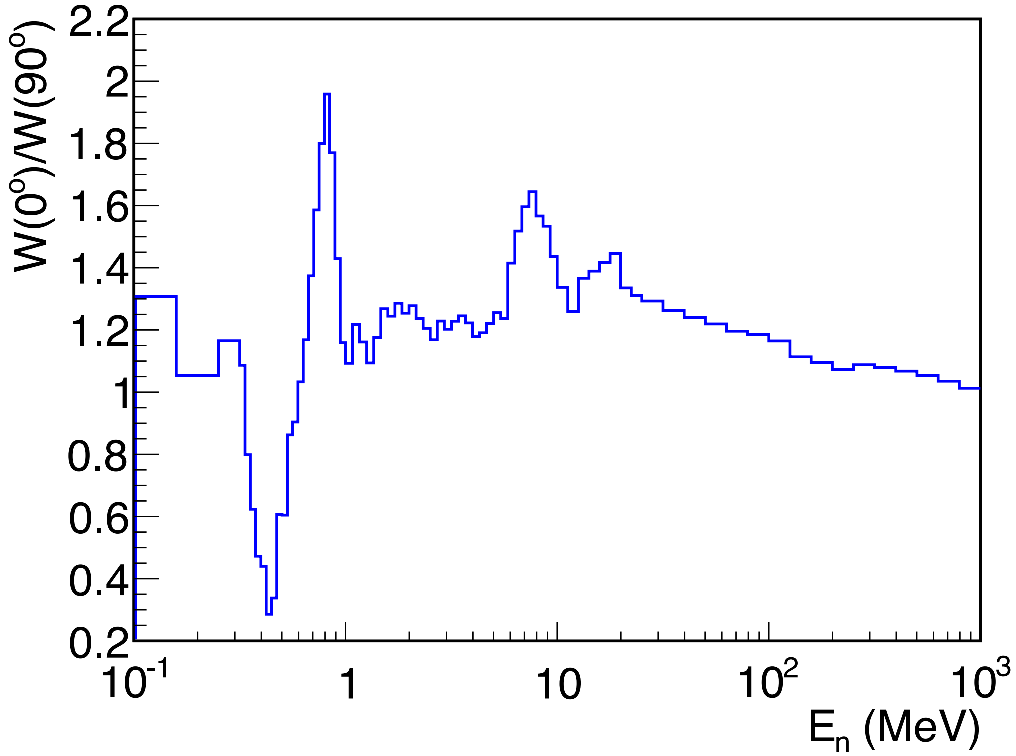
Fission Fragment Angular Distributions

FFAD at E_n > 300 MeV

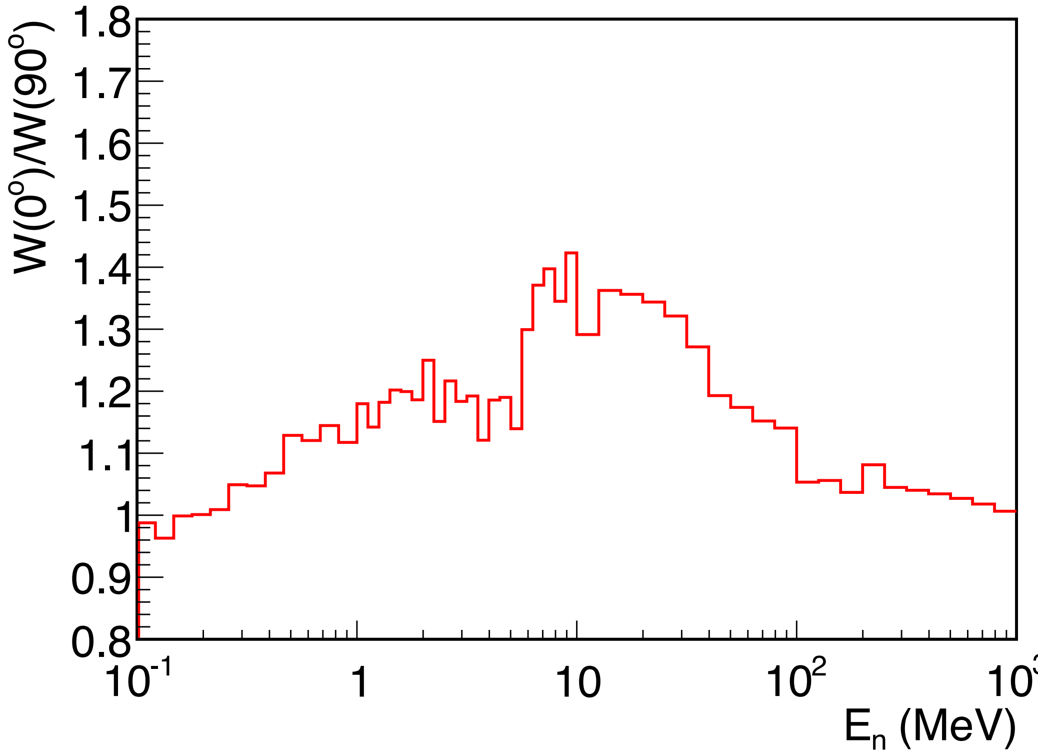
Above 300 MeV the pile-up and noise effects in the cathode signals avoid a good reconstruction of the FF trajectories.

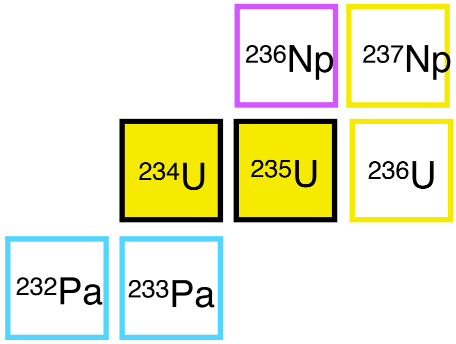
The **Anisotropy parameter** has been **linearly extrapolated** to the value of 1 at 1GeV.

$^{234}U(n,f)$:



$^{235}U(n,f)$:





Fission Fragment Angular Distributions

FFAD at E_n > 300 MeV

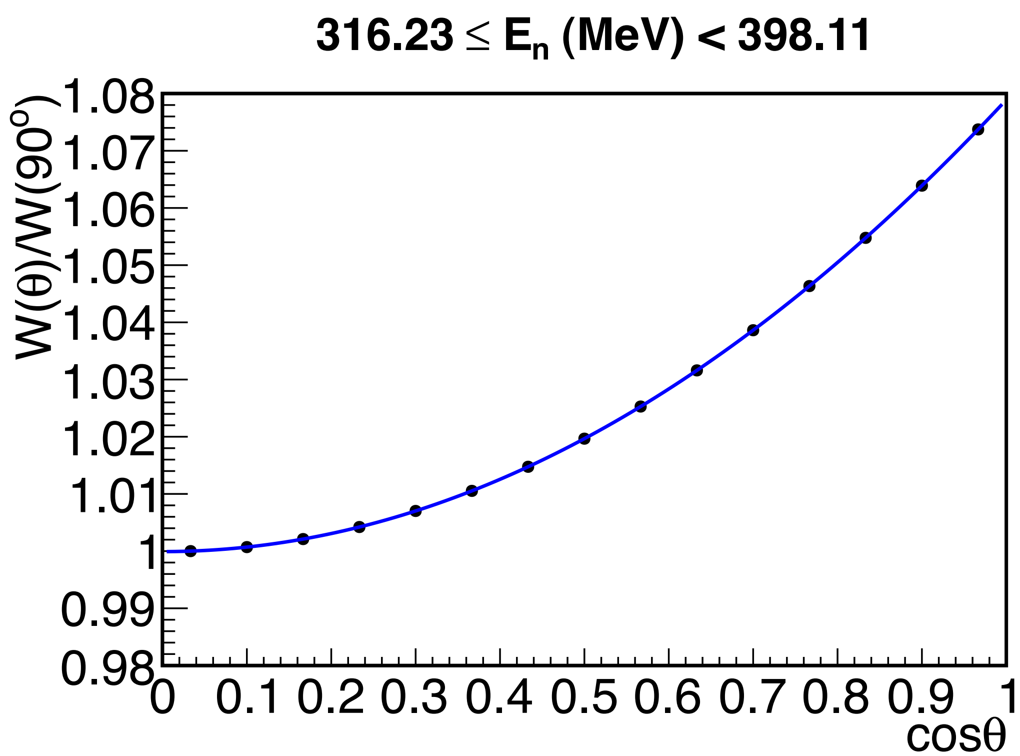
Above 300 MeV the pile-up and noise effects in the cathode signals avoid a good reconstruction of the FF trajectories.

The **Anisotropy parameter** has been **linearly extrapolated** to the value of 1 at 1GeV.

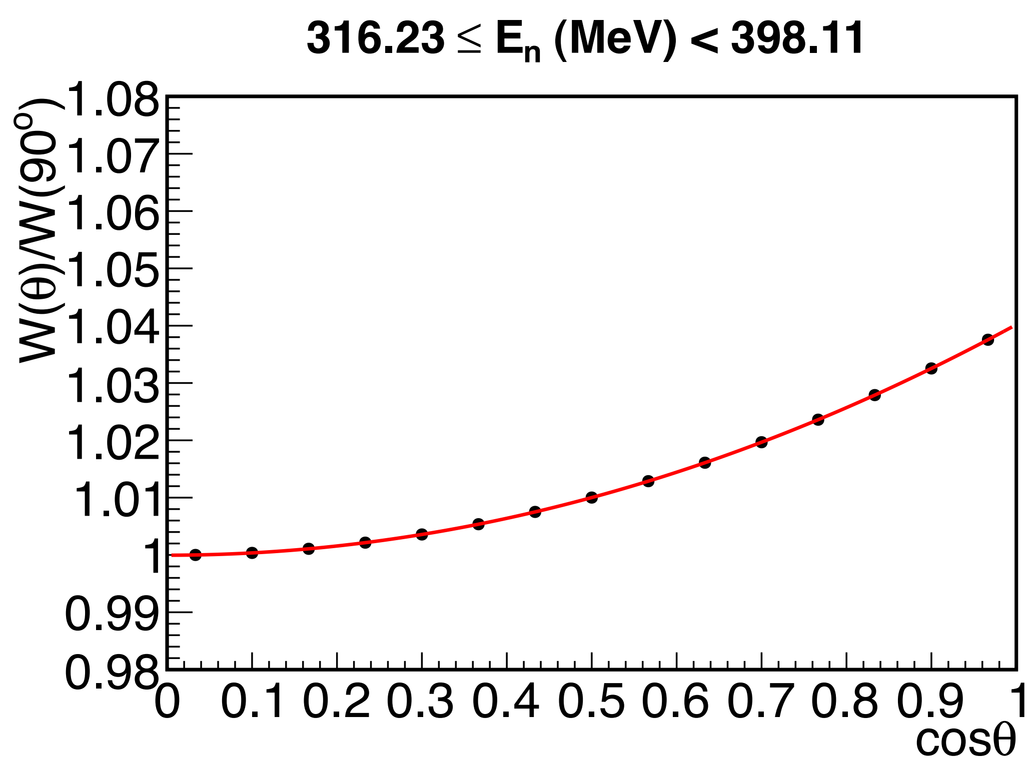
The **AD have been reconstructed** using the Legendre polynomials up to order 2:

$$W(\cos\theta) = A_0 \left[1 + \frac{A_2}{2} (3\cos\theta^2 - 1) \right] \quad \text{where:} \quad \frac{W(0^o)}{W(90^o)} = \frac{1 + A_2}{1 - \frac{1}{2} A_2}$$

$^{234}U(n,f)$:



$^{235}U(n,f)$:



Fission Fragment Angular Distributions

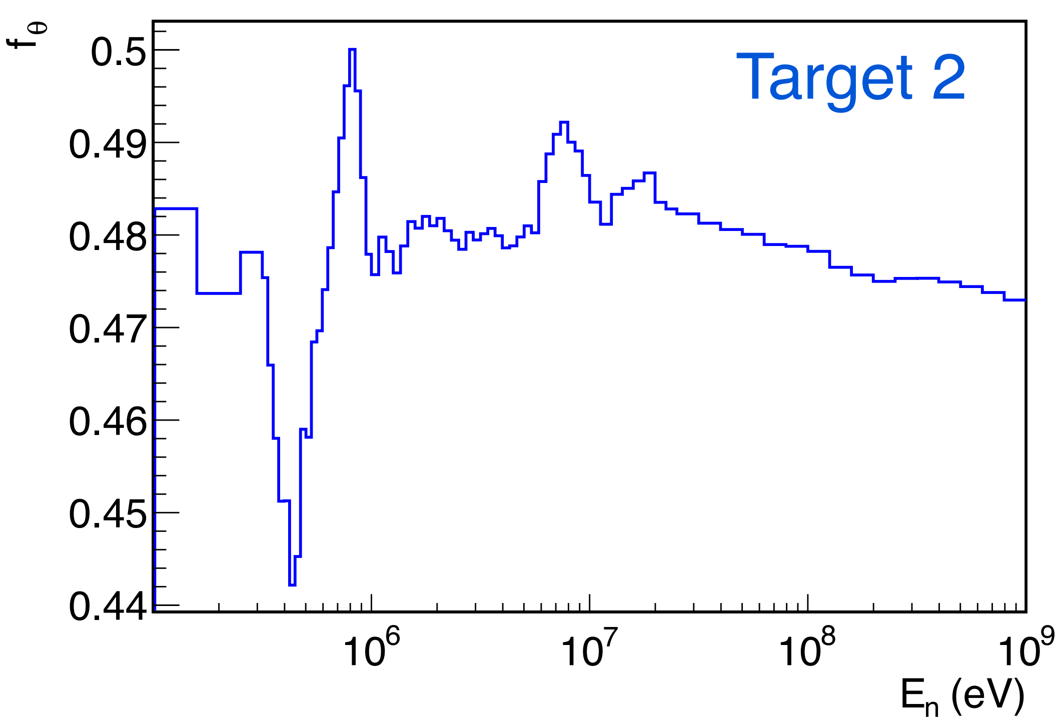
Efficiency correction factor

The **efficiency correction factor**, required to calculate the cross section, depends on the anisotropy of the emitted FF.

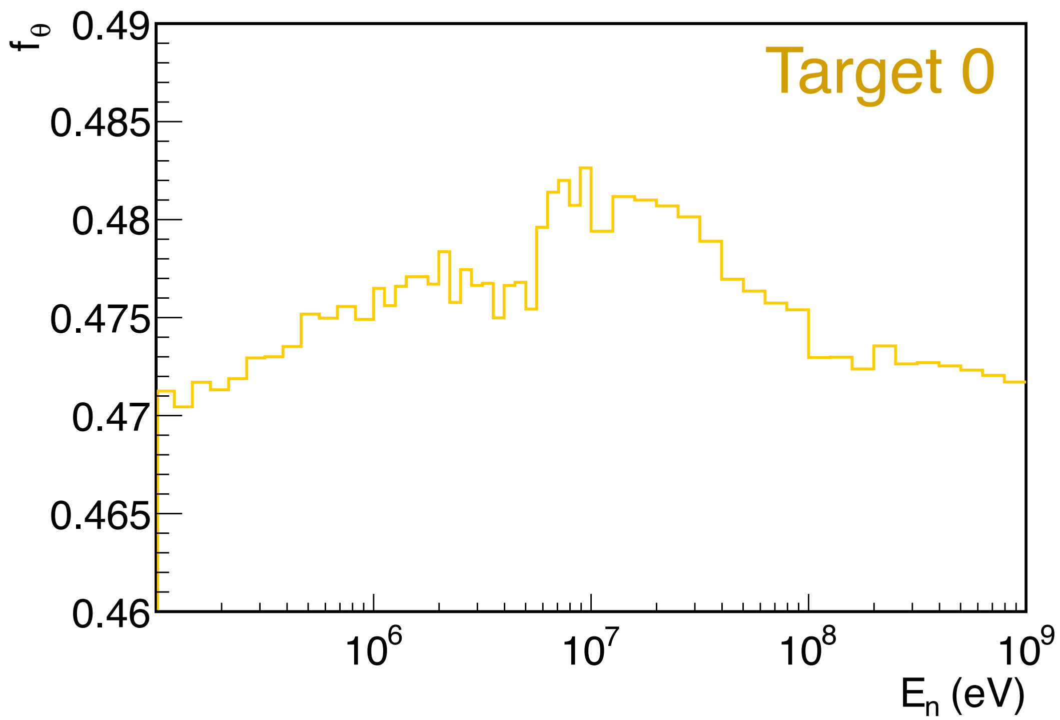
This factor (f_θ) is calculated as:

$$f(E_n)_\theta = \frac{\int_0^1 W(\theta) \cdot \varepsilon(\theta) \cdot d(cos\theta)}{\int_0^1 W(\theta) \cdot d(cos\theta)}$$

$^{234}U(n,f)$:



$^{235}U(n,f)$:



^{236}Np ^{237}Np
^{234}U ^{235}U ^{236}U
^{232}Pa ^{233}Pa

Fission cross section

Analysis at $E_n < 100$ keV

The fission count rate, defined as the number of detected fission events per unit of energy is:

$$C(E_n)_f = \sigma(E_n)_f \cdot N \cdot f(E_n)_f \cdot \Phi(E_n)$$

- Neutron flux distribution:
  - During the 2012 campaign the neutron flux was measured through the $^{10}B(n,\alpha)$ reaction up to 10 keV using a MGAS chamber [1] running in parallel with the PPAC.
  - The neutron flux measured in 2011 [2] has been used above this energy.
- The $^{234}U(n,f)$ cross section

The $^{234}U(n,f)$ cross section has been calculated assuming that all the targets receive the same neutron flux.

As the neutron flux received by the target during the measurement is not known, the neutron flux distribution has been properly normalised using the $^{235}U(n,f)$ reaction in the IAEA secondary standard energy region (7.8,11) eV.

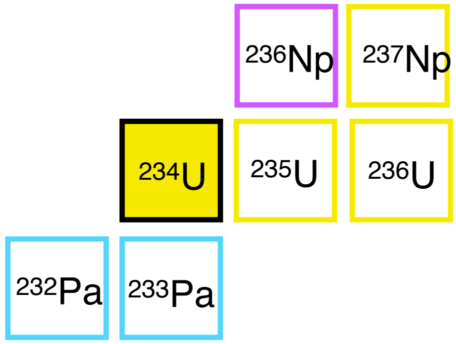
$$\sigma(E_n)_5 = \frac{C(E_n)_5}{\Phi(E_n) \cdot N_5 \cdot f(E_n)_5} \longrightarrow \sigma(E_n)_4 = \frac{C(E_n)_4}{\Phi(E_n) \cdot N_4 \cdot f(E_n)_4}$$

The $^{235}U(n,f)$ cross section results are presented in [3].

[1] M. Sabaté-Gilarte (internal communication).

[2] M. Barbagallo et al., Eur. Phys. J. A **49**:156 (2013).

[3] E. Leal-Cidoncha et al., EPJ Web of Conferences **146**, 04057 (2017).

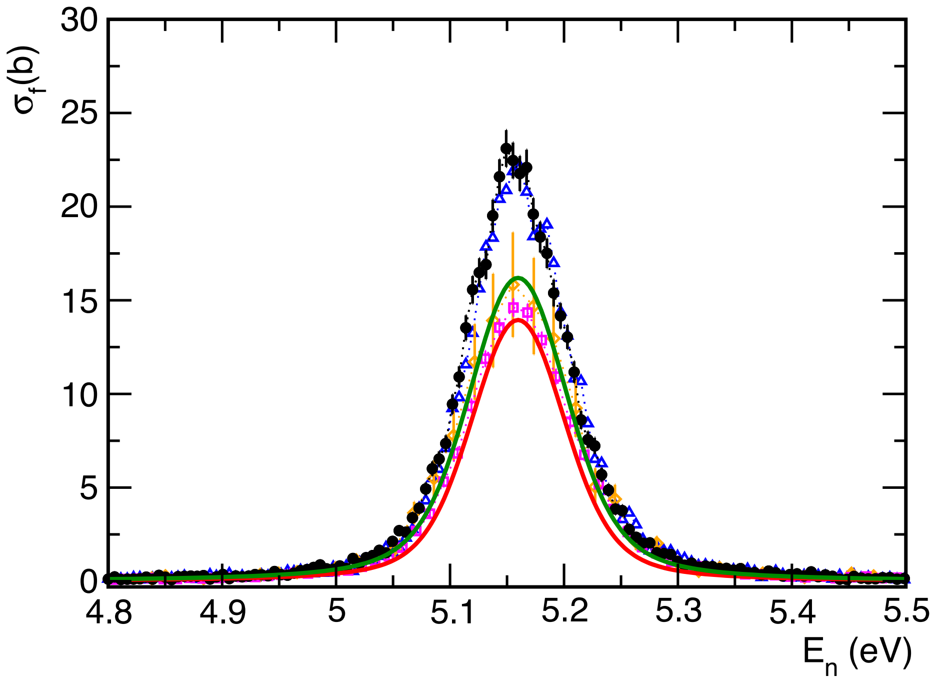


Fission cross section

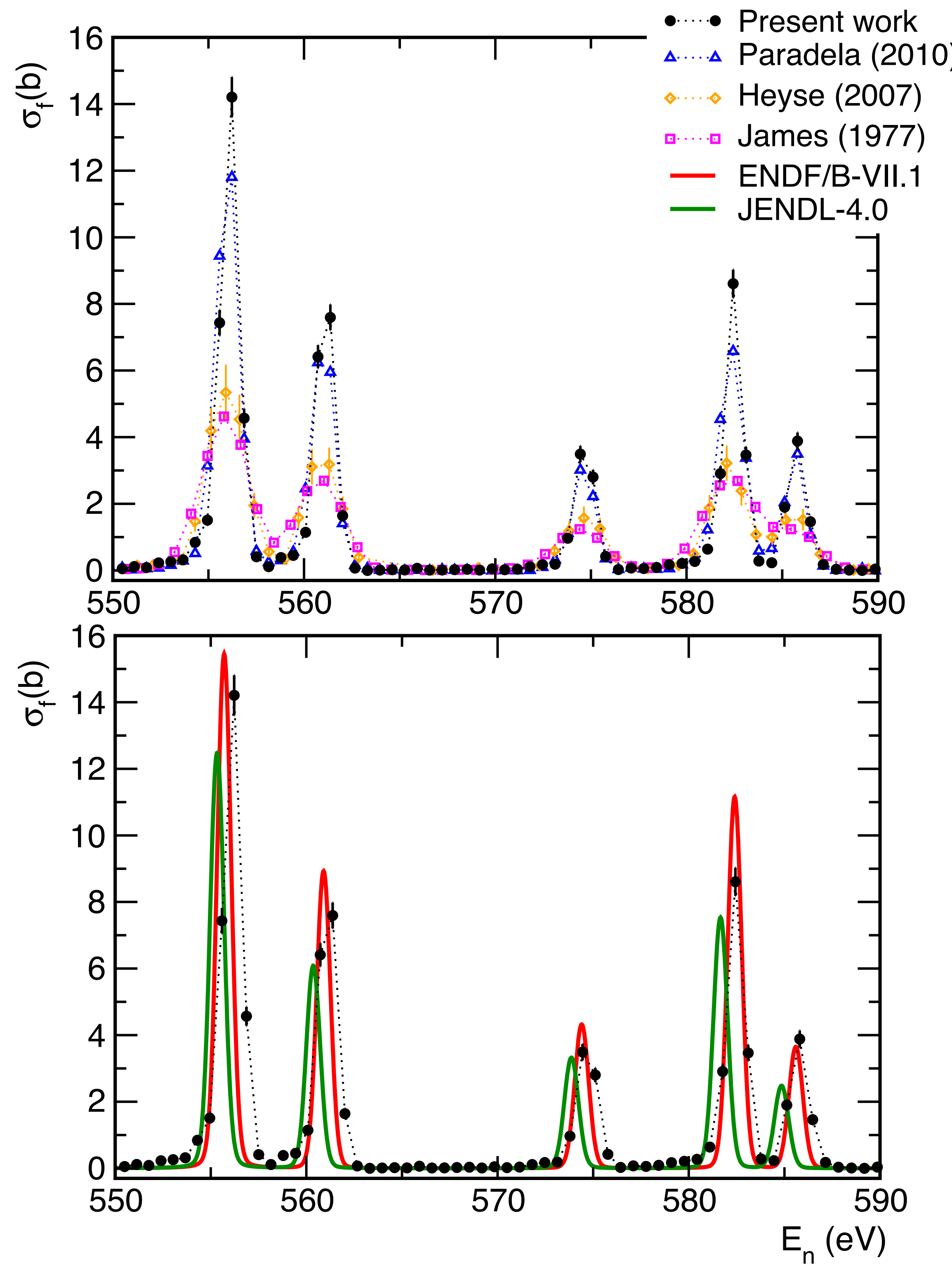
$^{234}U(n,f)$ results at E_n < 100 keV

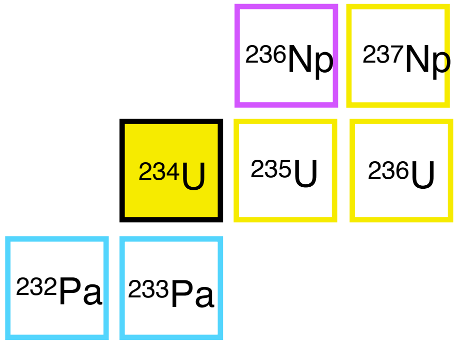
Resonance Region

- Resolved Resonance Region (RRR)
- Discrepancies found between the evaluations in energy and in the number of evaluated resonances.
- ENDF/B-VII.1 and JENDL-4.0 are based on the experimental data of James and this last one in the data of Heyse of the first resonance located at ~5.17 eV.



- The present data have a better resolution than the experimental data from James and Heyse, being in close agreement with the previous n_TOF data from Paradela.

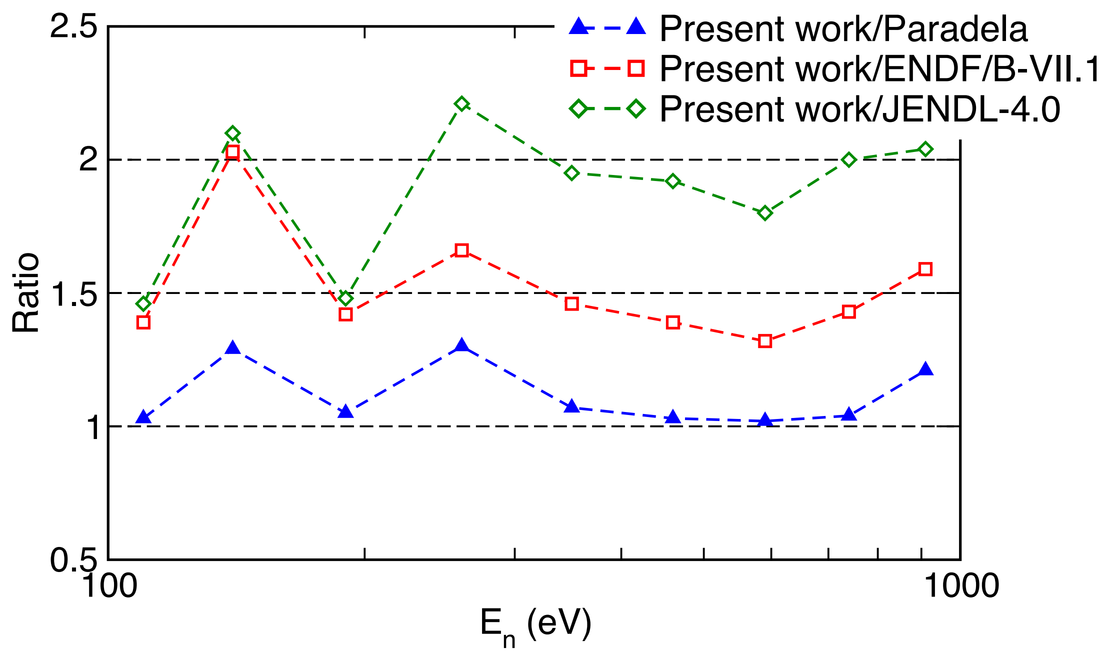


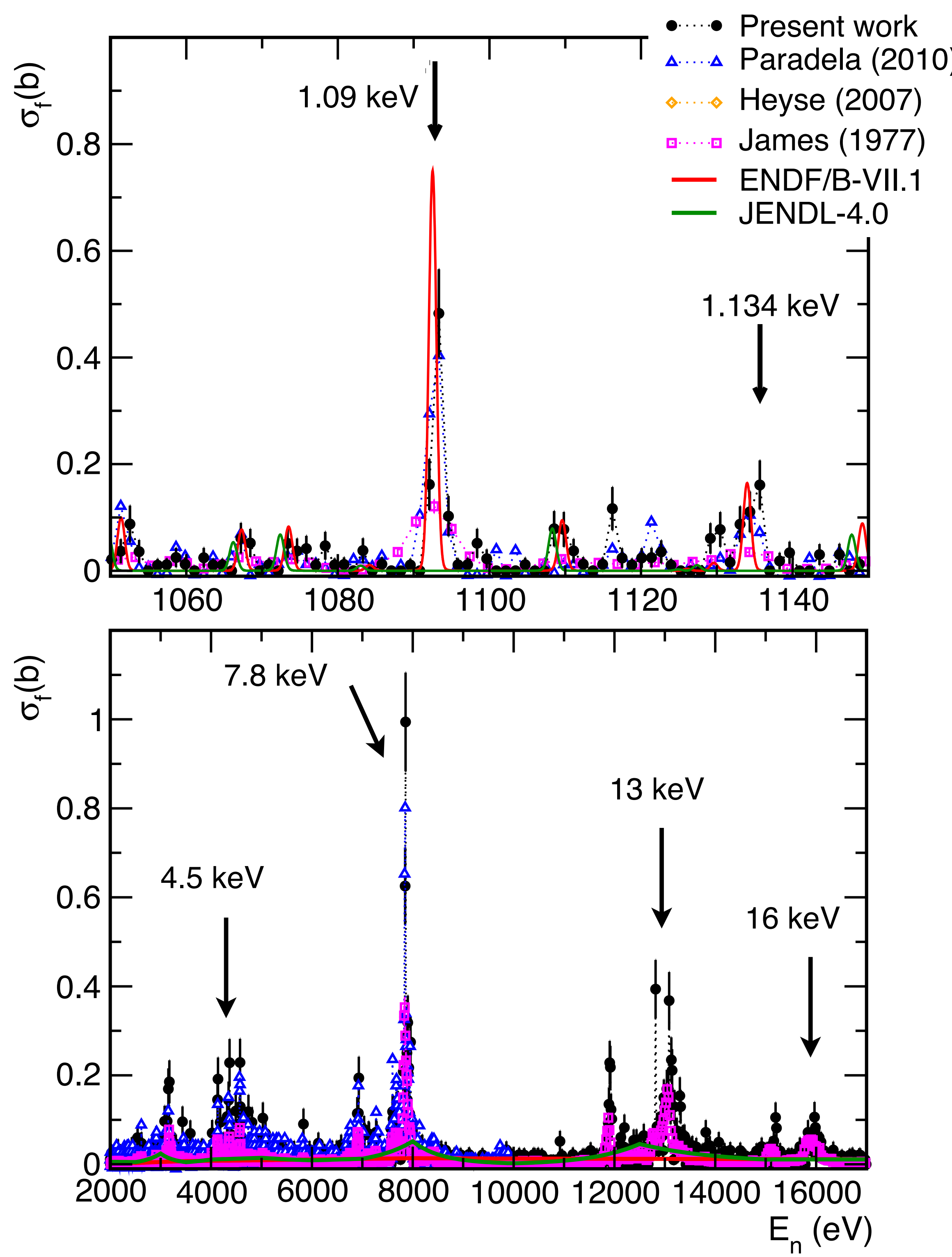


Fission cross section

^{234}U(n,f) results at E_n < 100 keV

- Two resonances have been obtained in this work in the keV region which are evaluated in ENDF/B-VII.1 and not in JENDL-4.0 at ~1.09 keV and ~1.134 keV.





- Unresolved Resonance Region (URR)
  - Some resonances are found in the experimental data in the URR, where the evaluations provide an average value of the cross section.
  - This is the case of the resonances found in the 10 keV region corresponding to **Class-II** levels.

236Np 237Np
234U 235U 236U
232Pa 233Pa

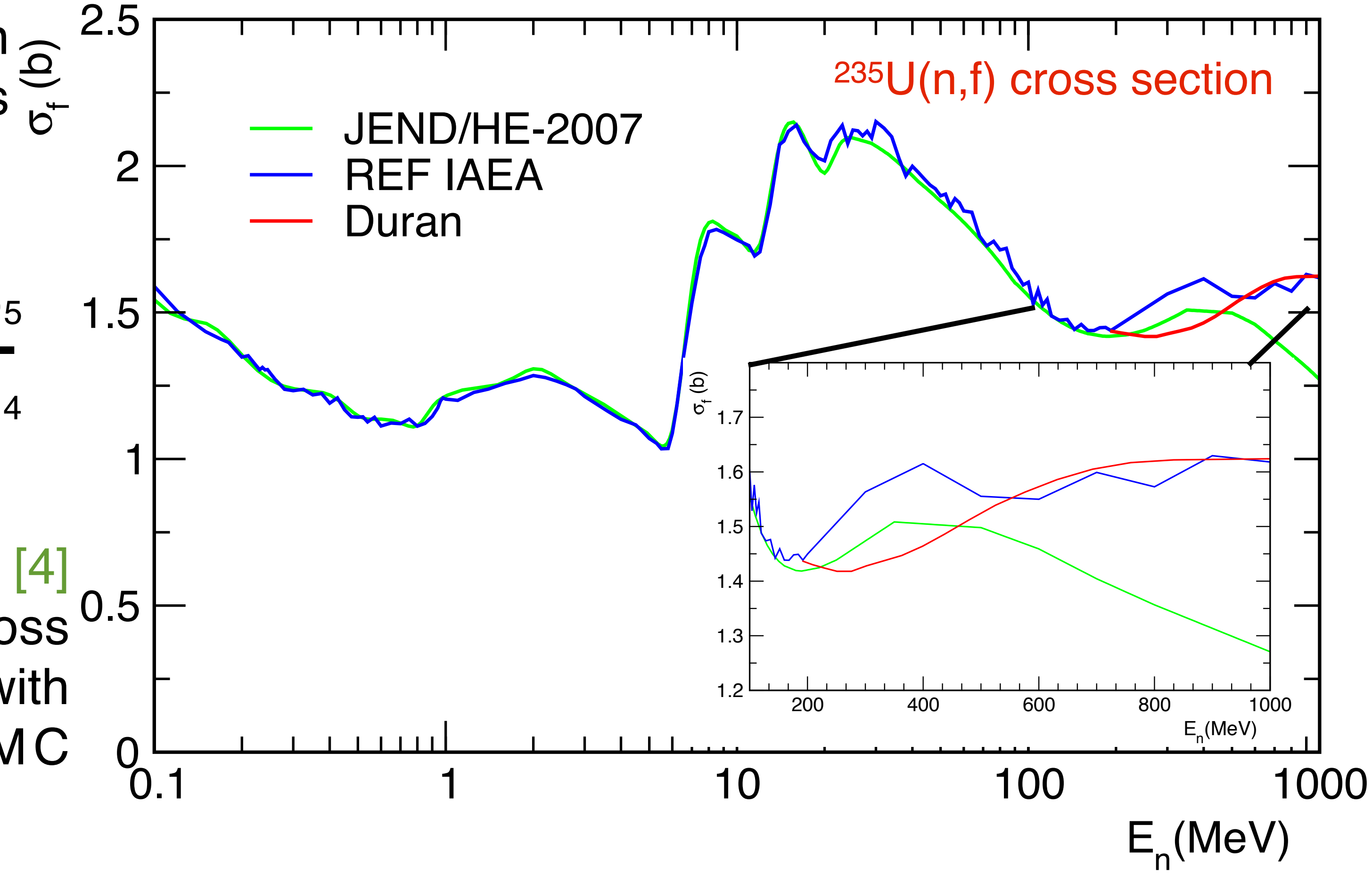
Fission cross section

Analysis at $E_n > 100$ keV

- The $^{234}U(n,f)$ cross section has been calculated relative to the $^{235}U(n,f)$ cross section through the **ratio $^{234}U/^{235}U$**, as:

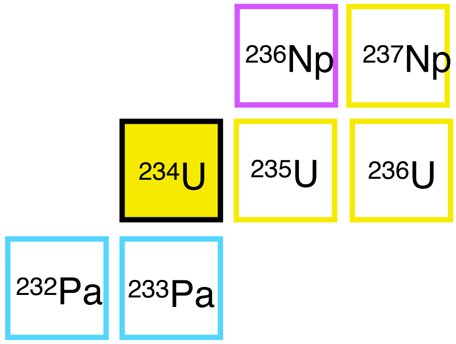
$$\sigma(E_n)_4 = \sigma(E_n)_5 \cdot \frac{\cancel{\Phi(E_n)} \cdot C(E_n)_4 \cdot N_5 \cdot f(E_n)_5}{\cancel{\Phi(E_n)} \cdot C(E_n)_5 \cdot N_4 \cdot f(E_n)_4}$$

- The recent work of Durán, Ventura et al. [4] combines the experimental n_TOF cross section ratios $^{209}Bi/^{235}U$ and $^{238}U/^{235}U$ with updated intra-nuclear cascade MC calculations.



- In this work the $^{235}U(n,f)$ cross section has been taken from → IAEA Ref. up to 200 MeV + Durán, Ventura et al. up to 1 GeV

[4] I. Durán et al., EPJ Web of Conferences **146**, 02032 (2017).

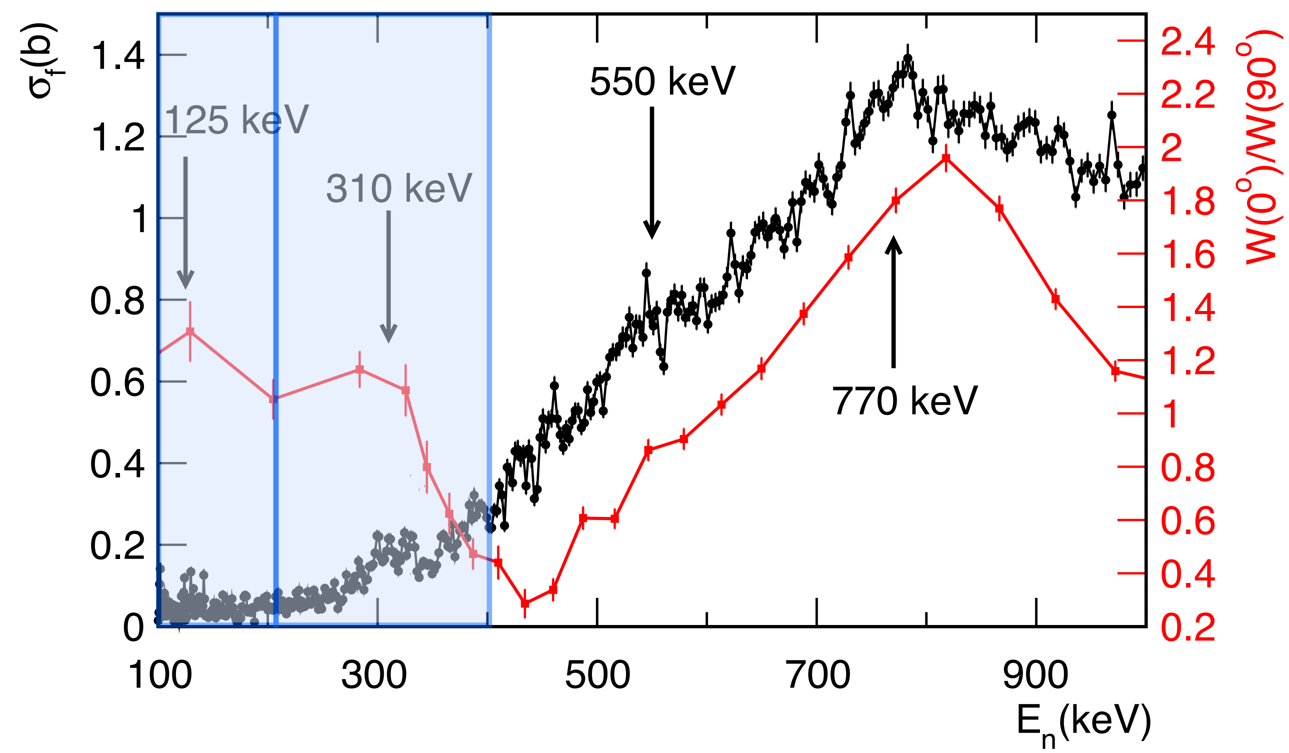


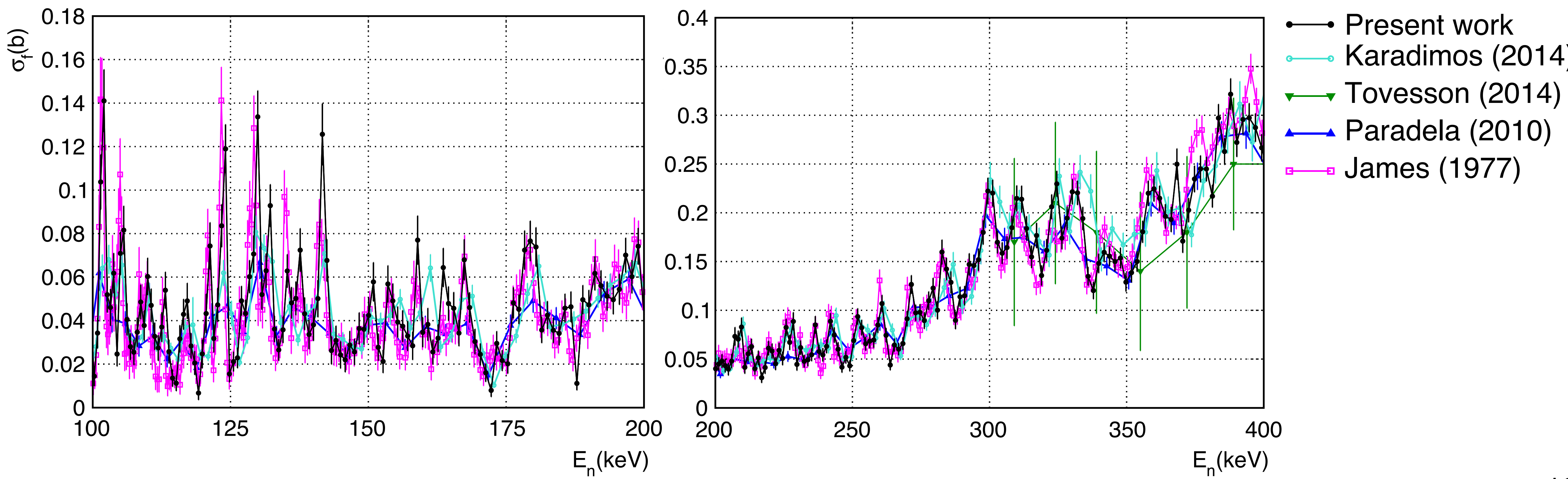
Fission cross section

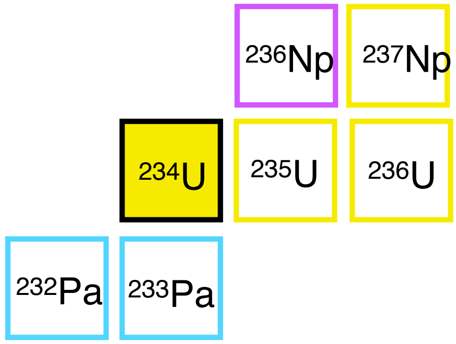
^{234}U(n,f) results at E_n > 100 keV

Threshold Region

- Some resonance-like **structures** have been observed in the threshold region that were claimed to correspond to **β vibrational levels** in the second/third wells.
- Structures at **125 keV** and **310 keV**:
  - The present data confirm the structures reported in the work of James.
  - The n_TOF data from Karadimos and Paradela could not resolve in detail these structures due to the low energy resolution although they confirm their existence.



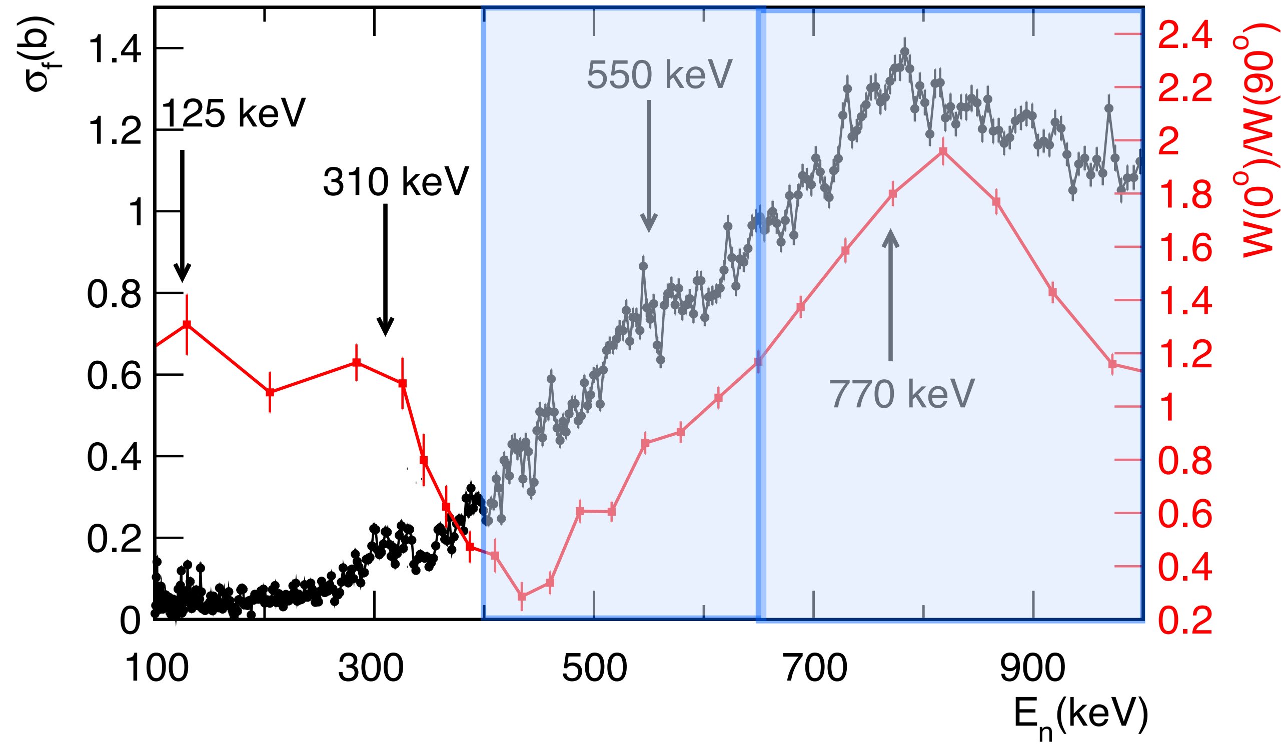


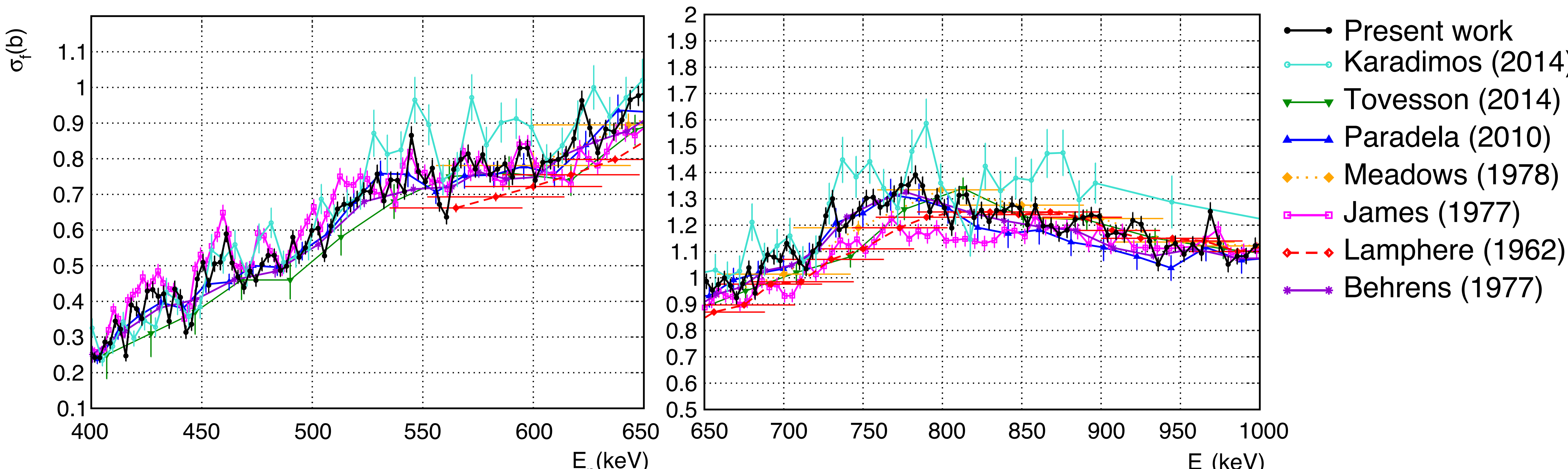


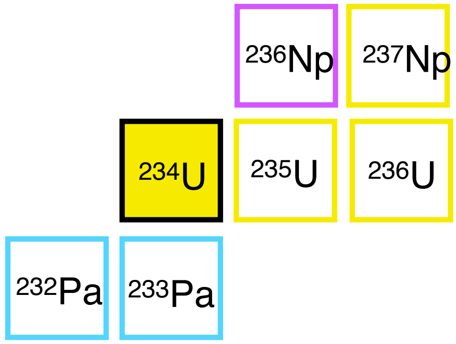
Fission cross section

^{234}U(n,f) results at E_n > 100 keV

- Structures at **550 keV** and **770 keV**:
  - The structures are confirmed up to 730 keV by James and Karadimos, however both are above the rest of datasets.
  - Large discrepancies with James at energies where the anisotropy is high.
  - The n_TOF data from Paradela could not resolve the structures in fine detail due to the low energy resolution. Good agreement found around 770 keV, where a fit of the EXFOR anisotropy parameter was used to correct the efficiency in that work.







Fission cross section

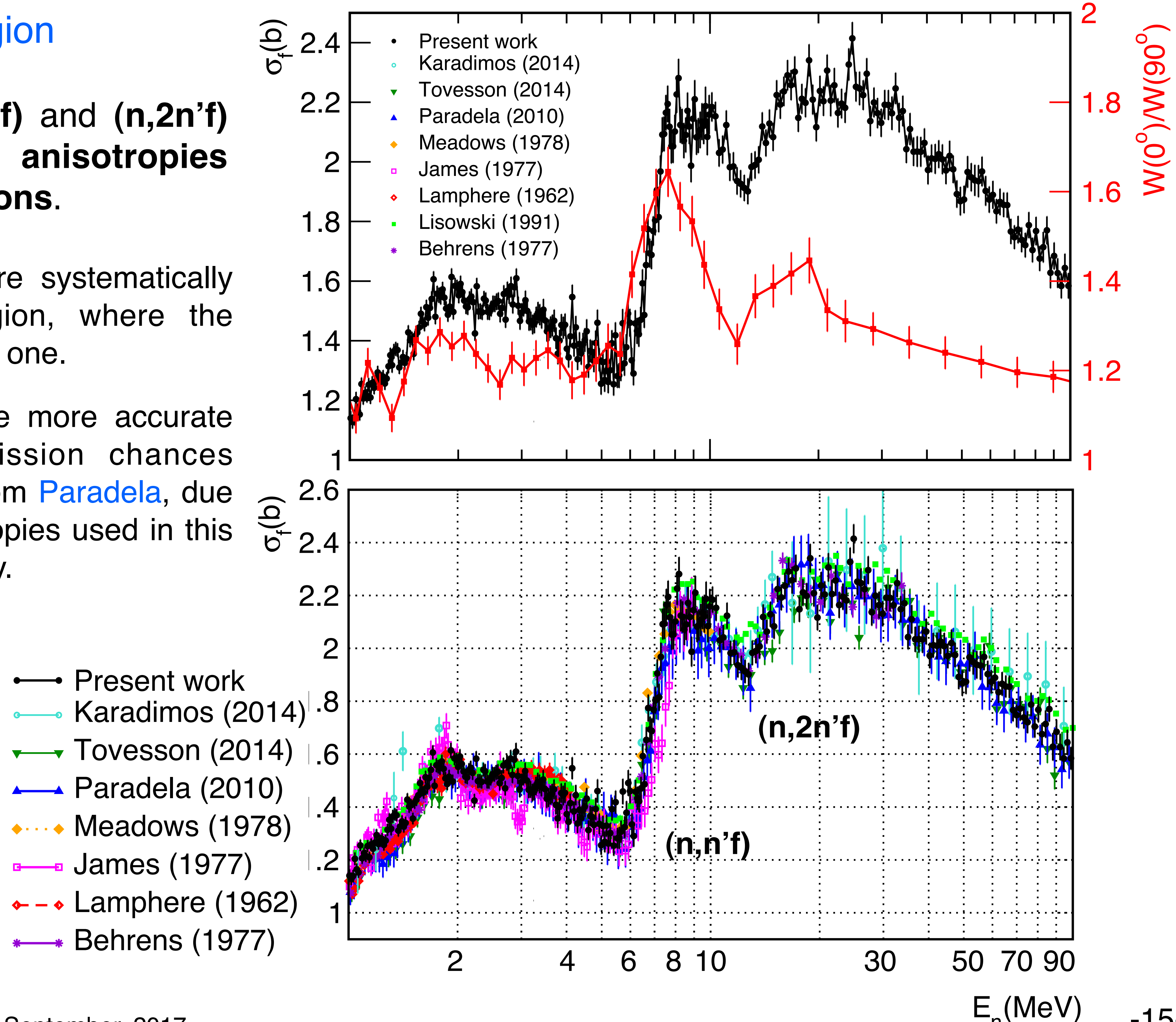
$^{234}U(n,f)$ results at E_n > 100 keV

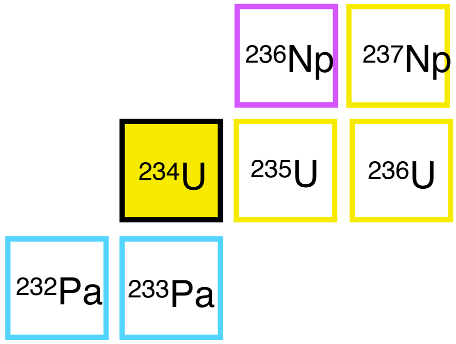
Fast neutrons energy region

• The opening of the **(n,n'f)** and **(n,2n'f)** channels produces **large anisotropies** and **increased cross sections**.

- The data from James are systematically lower in this energy region, where the anisotropies are higher than one.

- The present data provide more accurate cross sections in the fission chances thresholds than the data from Paradela, due to the experimental anisotropies used in this work to correct the efficiency.





Fission cross section

^{234}U(n,f) results at E_n > 100 keV

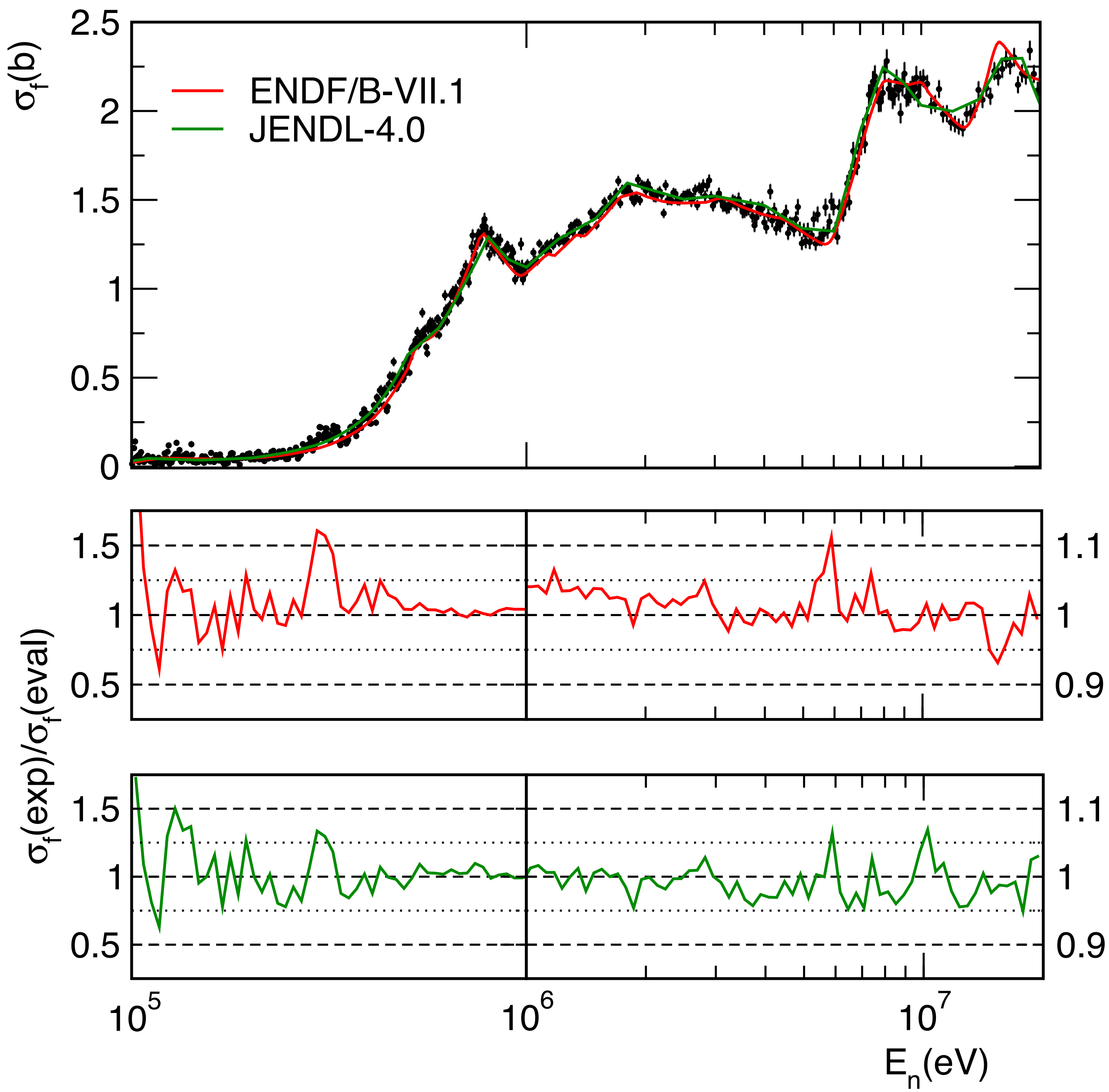
Evaluated cross sections

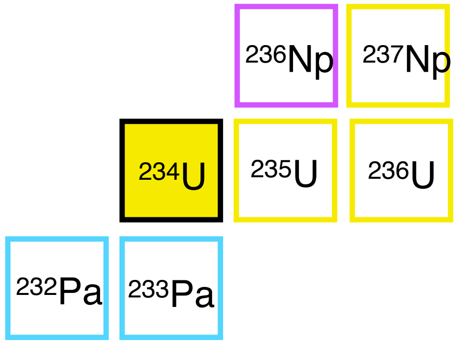
- The ^{234}U(n,f) cross section has been compared with the ENDF/B-VII.1 and JENDL-4.0 evaluations up to 20 MeV.

- Large differences have been found in the threshold region, where the evaluations provide an average value of the cross sections and, therefore the structures are not resolved.

  ~60% with ENDF/B-VII.1 (at 310 keV)
  ~30% with JENDL-4.0 (at 310 keV)

- In the few MeV region the present data are in closer agreement with JENDL-4.0, and the data from ENDF/B-VII.1 are ~5% below them.





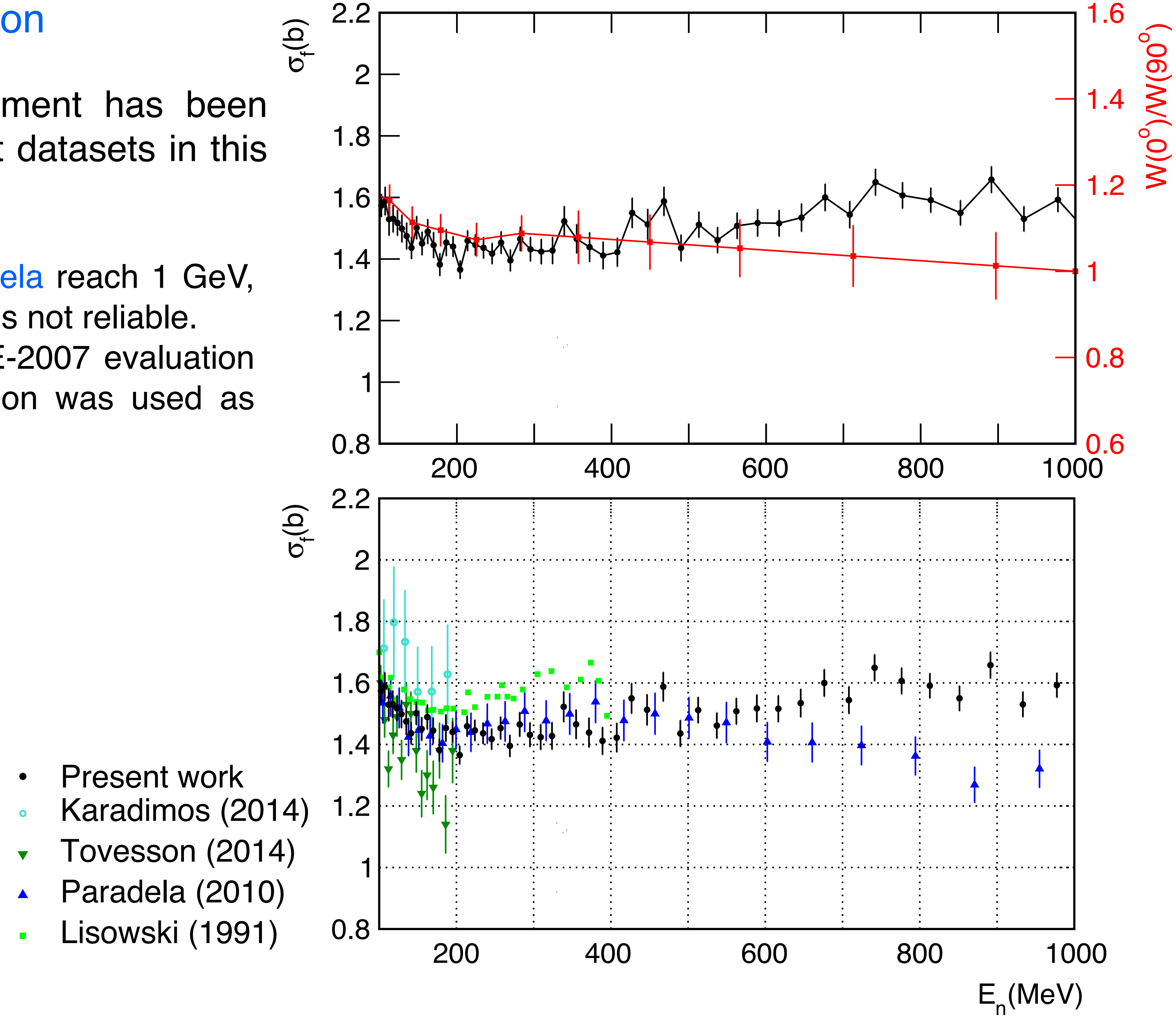
Fission cross section

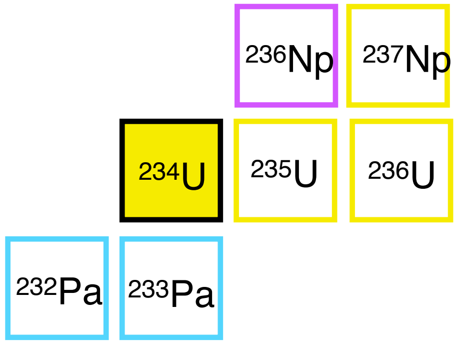
^{234}U(n,f) results at E_n > 100 keV

Intermediate energy region

- A considerable disagreement has been found between the different datasets in this energy region.

  - Only the data from Paradela reach 1 GeV, however above 500 MeV it is not reliable.
  In that work the JENDL/HE-2007 evaluation of the ^{235}U(n,f) cross section was used as reference.





Fission cross section

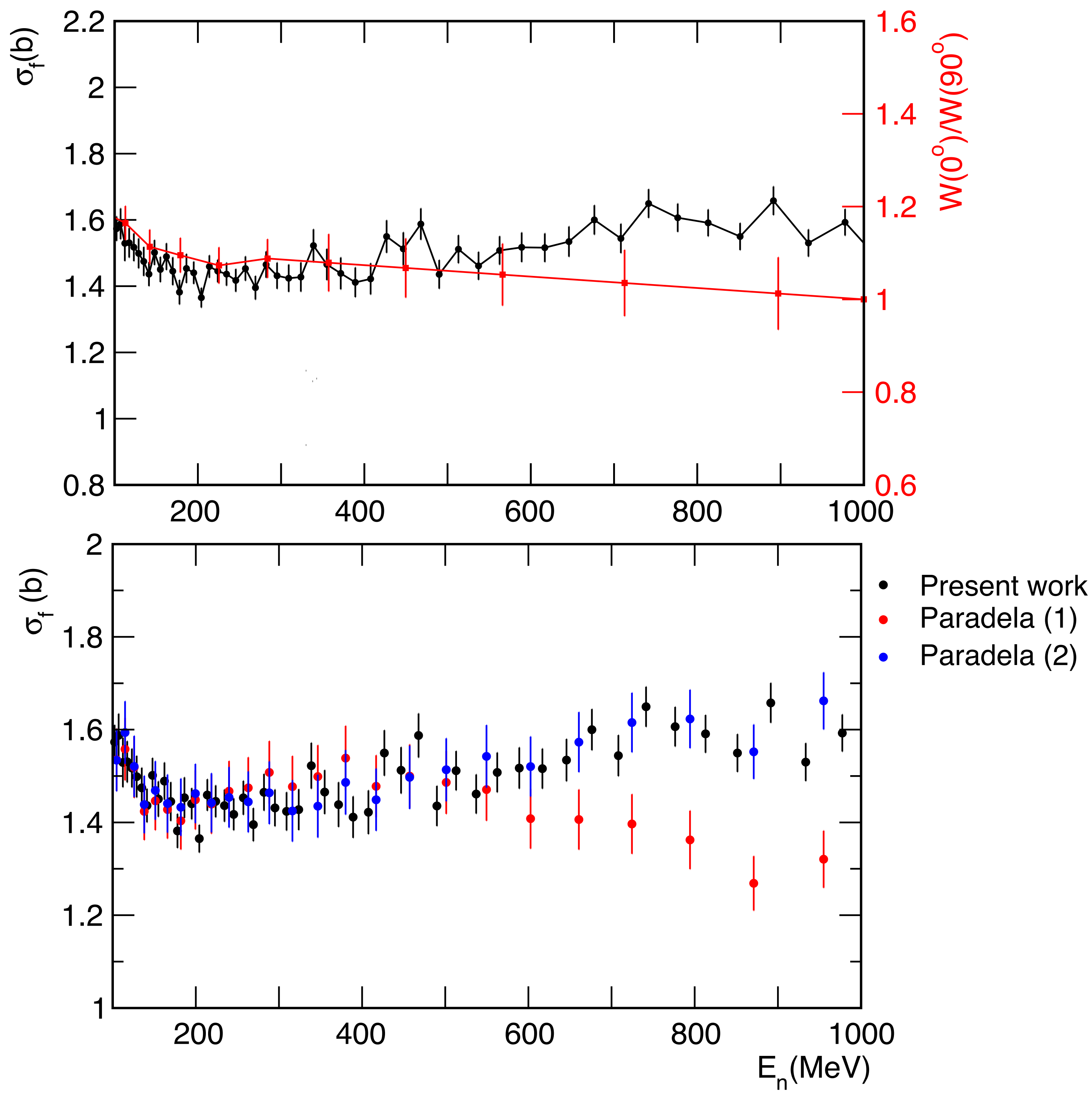
^{234}U(n,f) results at E_n > 100 keV

Intermediate energy region

- A considerable disagreement has been found between the different datasets in this energy region.

  - Only the data from Paradela reach 1 GeV, however above 500 MeV it is not reliable. In that work the JENDL/HE-2007 evaluation of the ^{235}U(n,f) cross section was used as reference.

  - In order to make an adequated comparison it has been recalculated using as reference the IAEA Ref + Durán et al.



Conclusion

- The FFAD have been measured with a high energy resolution in the full angular range providing more precise results than previous experimental data.
- Results of the ^{234}U(n,f) FFAD are provided in this work **for the first time** above 15 MeV covering the third chance region. In addition this is the first experimental measurement in the full energy range up to 300 MeV.
- The ^{235}U(n,f) FFAD and the anisotropy parameter has been calculated in the wide energy range up to 300 MeV.
- ^{234}U(n,f) cross section results are provided with better resolution in the RR than the fission experimental data used in the evaluations.
- Two resonances have been found in the ^{234}U(n,f) cross section in the RRR evaluated in ENDF/B-VII but not in JENDL-4.0 and some resonances corresponding to Class-II levels in the URR, where the evaluations provide an averaged cross section.
- The ^{234}U(n,f) cross section results in the threshold region allow to **resolve** in very fine detail the **structures** attributed to Class-II and Class-III levels.
- **Improved** cross section data are provided in the **fission-chances thresholds** due to the large anisotropies which have been experimentally obtained and included in the efficiency calculation in this work.
- The present cross section data are being analized in the Resonance Region using the R-Matrix code CONRAD in order to provide a theoretical description of the experimental data.

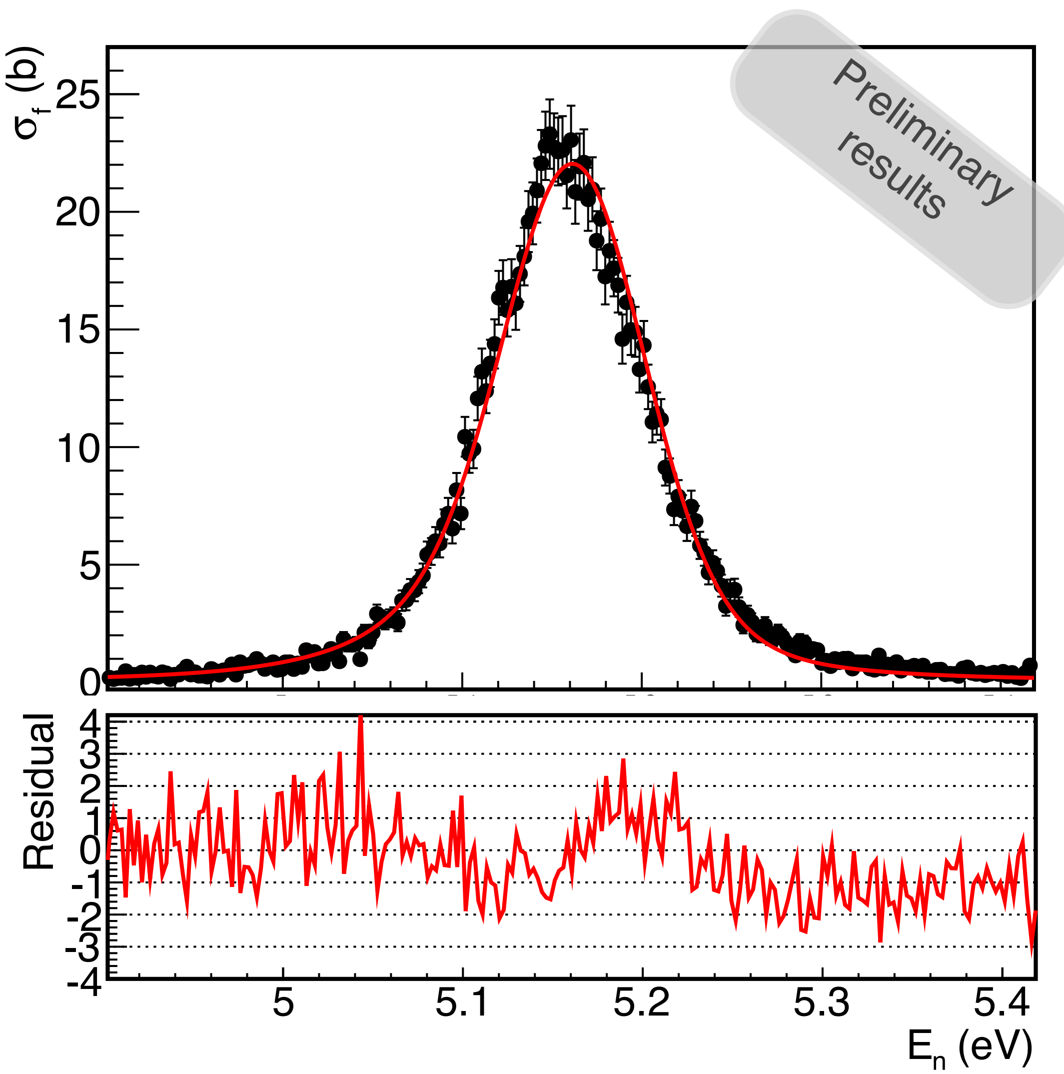
Outlook

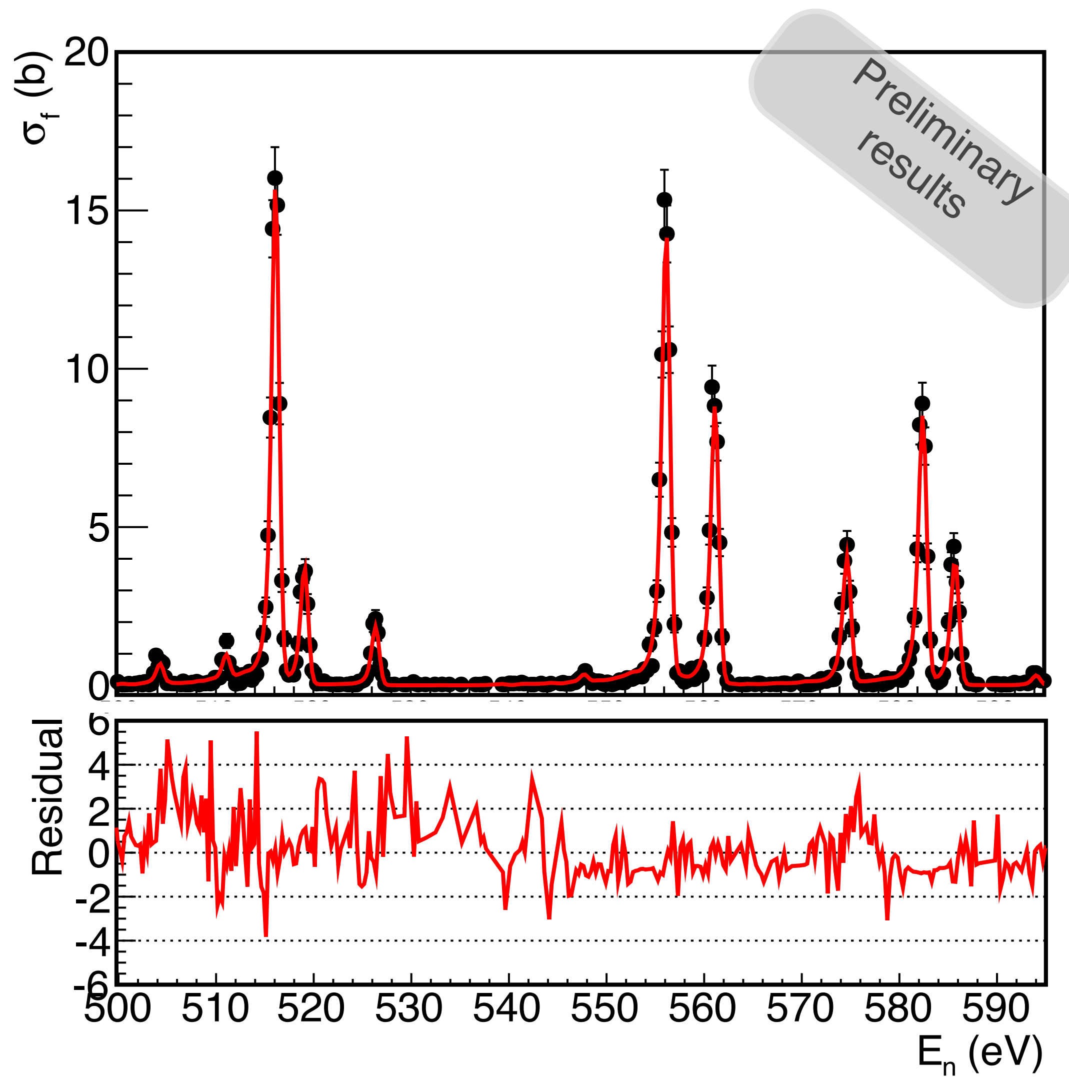
Resonance analysis - CONRAD

- The CONRAD* (COde for Nuclear Reaction Analysis and Dated Assimilation) R-Matrix code is been applied to analize the RRR up to 1 keV in order to provide a theoretical description of the experimental data.

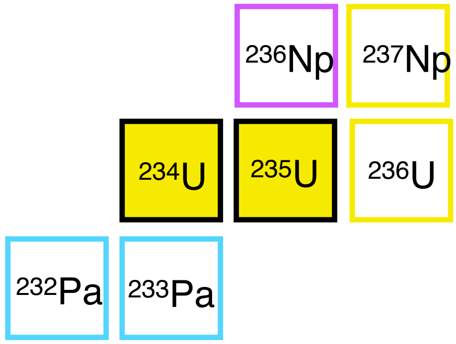
1) Penetration factor (P_{μ}):

1.1) Resonance analysis with P_{μ} =1.





** Developed at CEA/Cadarache*



Outlook

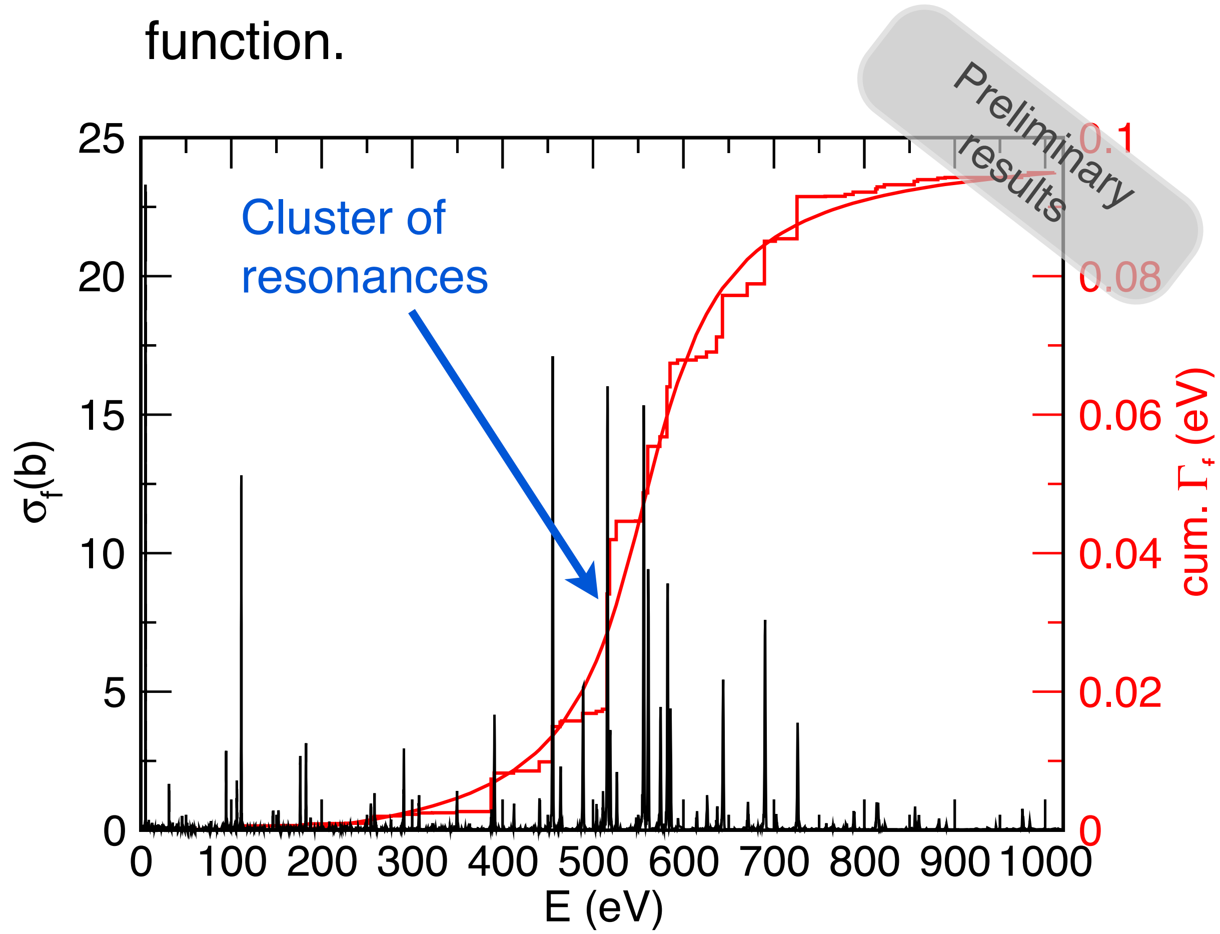
Resonance analysis - CONRAD

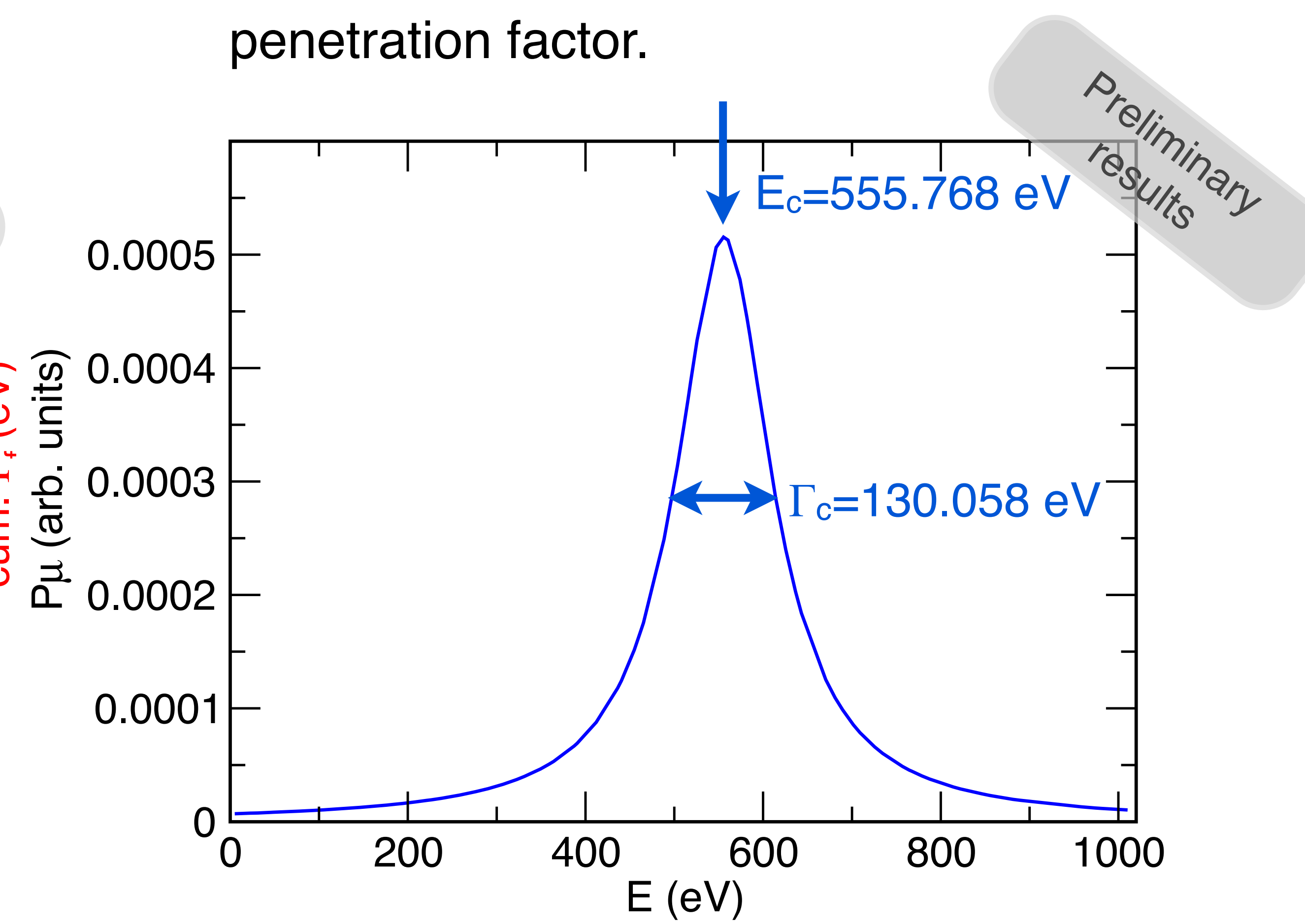
1.2) Resonance analysis with $P_{\mu} \neq 1$.

The penetration factor can be approximated by a **Lorentzian** function [5].

- The cumulative sum of Γ_f has been fitted to a cumulative Lorentzian function.

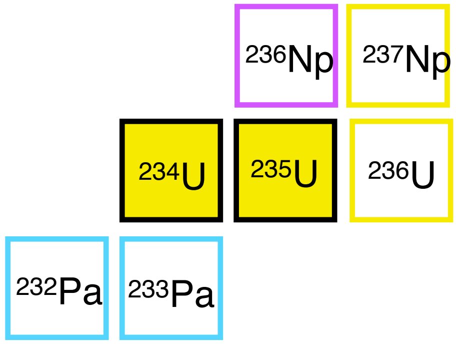
- The parameters obtained from the fit have been used to calculate the penetration factor.





Next step: CONRAD resonance analysis with the calculated $P_{\mu} \neq 1$.

[5] P. Tamagno, PhD. Thesis (2015).



^{234}U(n,f) measurement at CERN-n_TOF

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